بسم الله الرحمن الرحيم

تغير المناخ واستخدام المياه للري
في منطقة القصيم المملكة العربية السعودية

(رسالة دكتوراه مقدمة في جامعة إيست أنقليا بمدينة نورج - بريطانيا)

عبدالله عبدالرحمن المسند

1426

قسم الجغرافية - كلية العلوم العربية والاجتماعية

ملخص الرسالة

قام الباحث بتحليل حساسية استخدام المياه لري محصول القمح في القصيم لتتغير المناخي المستقبلي وذلك عبر دراسة تحليلية للمناخ الحالي اعتمادا على البيانات التاريخية لمنطقة الدراسة، والمناخ المستقبلي للقرن الواحد والعشرون اعتمادا على نتائج نماذج رياضية متقدمة.

الدراسة حللت البيانات المناخية لمنطقة الدراسة لثلاثين سنه ماضية (1971 – 2000) كما تم التركيز على درجة الحرارة و المطر ودراسة النزعة الإحصائية للبيانات المناخية، حيث دلت النتائج أن معدل درجة الحرارة في منطقة الدراسة يرتفع بمعدل 0.55 م في العقد الواحد، وأيضا ارتفاع في درجة الفروق بين درجة الحرارة الدنيا والقصوي 0.30 م في العقد، كما بلغ متوسط سقوط الأمطار 92 ملم خلال الفترة الزمنية المدروسة وتشير الدراسة إلى وجود ارتفاع طفيف في معدل سقوط الأمطار تصل إلى 3 ملم في العقد.

كما استعرضت الدراسة المياه الجوفية في منطقة القصيم مع التركيز على أهم التكوينات الجوفية مع الإشارة إلى مشاريع تحلية المياه الضخمة والسدود المنشأة، ومن خلال دراسة البيانات التاريخية أثبتت الدراسة أن هناك انخفاض مستمر في المياه الجوفية العميقة خلال العشرين سنه الأخيرة على سبيل المثال بئر 5 ضمن آبار المختارة للدراسة أنخفض مستوى سطح الماء 71 متراً خلال 23 سنه الماضية.

علاوة على ذلك قام الباحث بدراسة ميدانية مقارنة بين المزارع التقليدية والمز را ع التجارية لقياس الكمية المستخدمة من المياه لري محصول القمح والتي تتراوح في المزارع التقليدية 12663 و 18874 م3 /هكتار / فصل النمو، وفي المزارع التجارية 7100 و 9341 م3 /هكتار / فصل النمو. كما قام الباحث بتحليل التربة والمياه في مختبرات جامعة القصيم، وحساب الإنتاجية للمحصول، و كفاءة استخدام الماء، وجدولة الري المثالية ومقارنتها بالفعلية كما أجرى الباحث إستبانة بين المزارعين لدراسة ابرز المشاكل التي تواجه مزارعي القمح بشكل خاص.

أيضا الدراسة حسبت البخرنتح و من ثم الاحتياجات المائية المثالية لمحصول القمح وفقاً للمناخ الحالي مستخدماً أحدث الطرق الإحصائية معتمداً على منهج منظمة الفاو. كما حسب البخرنتح و الاحتياجات المائية لمحصول القمح لفترة مستقبلية 2020 و 2080 اعتمادا على مخرجات ثلاثة نماذج رياضية تعنى باستقراء المناخ المستقبلي وهي HadCM3و CGCM2 و ECHAM4. دلت النتائج أن ارتفاع الحرارة 1.3 م عام 2020 سيؤدي إلى ارتفاع البخرنتح 3% وارتفاعها 4.1 م عام 2080 سيؤدي إلى ارتفاع البخرنتح 9% - 12% وفقاً لاختلاف السيناريوهلت المستخدمة في الدراسة. كما دلت النتائج أن الاحتياجات المائية لمحصول القمح سترتفع تبعا لارتفاع درجة الحرارة 3% عام 2020 و ما بين 9% - 12% عام 2080. أثبتت الدراسة أن ارتفاع الحرارة

درجة واحدة فقط يقود إلى ارتفاع الاحتياجات المائية لمحصول القمح 103 م3 /هكتار / فصل النمو.

أخيراً أثبتت نتائج النماذج الرياضية الثلاث المستخدمة أن درجة الحرارة سترتفع في منطقة الدراسة حوالي 0.99 م – 1.54 م عام 2020 وفي عام 2080 يقدر الارتفاع بين 3.15 م – 4.99 م كما أشارت نتائج تحليل التغيير المناخي أن منطقة القصيم.

CLIMATE CHANGE AND WATER USE FOR IRRIGATION: A CASE STUDY IN THE GASSIM AREA OF SAUDI ARABIA

Abdullah Almisnid

July 2005

A thesis submitted to the School of Development Studies at the University of East Anglia in fulfilment of the requirements for the degree of Ph.D.

CLIMATE CHANGE AND WATER USE FOR IRRIGATION: A CASE STUDY IN THE GASSIM AREA OF SAUDI ARABIA

Abdullah Almisnid

2005

Abstract

This thesis describes an assessment of the sensitivity of water use in irrigation to climate change in the Gassim area of Saudi Arabia. The thesis examines observed climate variability (1971–2000). Estimates of crop water requirements (CWR) for wheat under current climate conditions are presented along with results of field studies of irrigation water use on both traditional and commercial farms. Outputs from three General Circulation Models (GCMs) HadCM3, CGCM2 and ECHAM4 for current (control) and future (2020s and 2080s) are analysed. Changes in temperature, relative humidity, wind speed and sunshine duration are used to calculate future changes in evapotranspiration (ET_O) and CWR for wheat.

Observed temperature in Gassim (1971-2000) shows a positive trend with a rate of warming of 0.55°C/decade and an increase in Diurnal Temperature Range (DTR) (0.30°C/decade). The average annual rainfall is 92 mm, there is a slight positive trend in rainfall, and the average rate of increase is 3 mm/decade. Records of groundwater levels in the region highlight a sustained rapid decline during the last 20 years. Fieldwork results examine the actual water applied (AWA) and the relative productivity for wheat. ET_O and CWR are estimated based on the FAO approach for the observed climate, and comparisons are made between these and AWA.

Climate change scenarios are presented for Saudi Arabia, and Gassim, using the outputs of the three GCMs with two emissions scenarios (A2, high, and B2, low). Warming by the 2020s, in comparison to the baseline climate, is between 1°C and 1.5°C, and by the 2080s, the range is between 3.2°C and 4.9°C, In terms of rainfall, there is no significant change (annual changes range from -1.7 to 14.9% and from -9.4 to 17.4% in the 2020s and 2080s, respectively).

ET_O and CWR are projected to increase by about 3% by the 2020s, and by about 12% (A2) and 9% (B2) by the 2080s. A small increase in temperature such as 1°C could result in an increase in CWR of about 103 m^3/ha/season for wheat in Gassim.

This is the first integrated study into the possible impacts of climate change on agricultural water use in the region. Gassim, given no significant increase in rainfall, will have higher irrigation needs than under even the current climate conditions, which will put water use for irrigation under greater pressure. Results from interviews with farm owners and labourers on water use and climate change highlighted the importance of non-climate factors such as water management.

Acknowledgements

My first acknowledgement is to Allah who guides and protects me, and through whose mercy I was able to accomplish this project.

Secondly, I would like to thank **Declan Conway, Jean Palutikof**, and **Bruce Lankford** who have been excellent and ideal supervisors during the period of my PhD study. Their comments and advice have been much appreciated, and I am extremely grateful for their tireless efforts on my behalf; without their guidance this work would never have come to fruition.

I would also like to thank the many colleagues and friends in the Climatic Research Unit who have supported me over the years: Mansour Almazroui, Mike Salmon, Stephen Blenkinsop, Naser Sarhan, Tom Holt, David Viner, David Lister, and Mohammah Sidup Sirabaha; your suggestions and encouragement have been invaluable. Special thanks to Steve Jones for correcting my grammar.

I would also like to express my gratitude to the following people for their support: Mohammad Kassem, Abdularahman Alwasel, and Mohammad Abdulaziz.

Thanks are also due to the School of Development Studies and the Climatic Research Unit at UEA for their encouragement, and to Gassim University who lent me the necessary equipment for use in the fieldwork. Acknowledgments are also due to the staff members of the Geography Department in Gassim University and to the members of the Meteorology Department in Jeddah. My thanks also to the Ministry of Agriculture and Water in Riyadh, and the Agricultural Research Centre in Unaizah. I would also like to thank the Saudi Arabian Cultural Bureau in London for their contributions and assistance.

Finally, a very special thanks to my family and to all my friends in Norwich and Saudi Arabia for their help. Most especially to my parents for their prayers, support and encouragement; may Allah reward them.

List of Acronyms, Abbreviations, and Units

AWA	Actual Water Applied
A2	Scenario A2
B2	Scenario B2
C	CGCM2
CFC	Chlorofluorocarbon
CFs	Commercial Farms
CH^4	Methane
CO_2	Carbon Dioxide
cP	Continental Polar
cT	Continental Tropical
CWR	Crop Water Requirements
CWUE	Crop Water Use Efficiency
DDC	Data Distribution Centre
DTR	Diurnal Temperature Range
E	ECHAM4
ECe	Electrical Conductivity in Saturation Extract (mmhos/cm)
ECw	Electrical Conductivity of Irrigation Water (mmhos/cm)
Eff	Efficiency of the Irrigation Method
ETo	Reference Evapotranspiration
FAO	Food and Agricultural Organization
FWUE	Field Water Use Efficiency
GCM	General Circulation Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIR	Gross Irrigation Requirement
GIS	Geographical Information System
H	HadCM3
Ha	Hectare
IE	Irrigation Efficiency
IPCC	Intergovernmental Panel on Climate Change
IS	Irrigation Scheduling
Kc	Crop factor in evapotranspiration calculations
LR	Leaching Requirement
LWGS	Length of the Wheat Growing Season
MAW	Ministry of Agriculture and Water
mP	Maritime Polar
N_2O	Nitrous Oxide
O_3	Ozone
PM	Penman-Monteith
RH	Relative Humidity
SO_2	Sulphur Dioxide
SRES	Special Report on Emissions Scenarios
Std	Standard Deviation
Temp	Temperature
TFs	Traditional Farms
Tmax	Maximum Temperature
Tmin	Minimum Temperature
WMO	World Meteorological Organization

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Chapter One: Introduction

1.1 Introduction

The Kingdom of Saudi Arabia, located in south-western Asia, is a vast landmass; it is the world's thirteenth largest country covering approximately 2.25 million km^2. Saudi Arabia occupies about 80% of the Arabian Peninsula, with a population of almost 22.7 million inhabitants in 2004 (Saudi Press Agency, 2004). It is bounded by the Red Sea and the Gulf of Aqaba to the west, Yemen and Oman to the south, Qatar, the United Arab Emirates and the Arabian Gulf (also known as the Persian Gulf) to the east, Kuwait, Iraq and Jordan to the north (Figure 1.1).

Figure 1.1: A general map of Saudi Arabia, and location of main case study area, Gassim (Abacci Atlas, 2004).

Saudi Arabia is a poor country in terms of agricultural potential and water resources, relative to its considerable size; the natural agricultural area is very limited; and indeed, cultivated land accounts for less than 1% of the total area (Alkolibi, 2002). Improvement in the agricultural sector (in both traditional and commercial farms) in Saudi Arabia has not been as successful as was planned, and this may be due to the fact that agriculture in Saudi Arabia experiences significant pressure from various sources. Many of these are related to the climate, such as extreme weather conditions and scarcity of water, which together present the Kingdom's farmers with major challenges. It is also the case that, these difficulties may be compounded in the coming decades by climate change, which is now generally accepted by the scientific community worldwide as being increasingly likely (for example, IPCC, 2000a).

The major climatic influences in Saudi Arabia are the extremely dry conditions, and the very high daytime temperatures, which often exceed 50°C in summer. There is a severe lack of permanent surface water resources typical of its location in an arid zone with low rainfall (annual average about 100 mm/year). The rainfall that does occur is unpredictable in quantity and irregular in occurrence, sand storms also often occur, and potential evaporation rates are very high (annual average about 3,500 mm, Alsharhan et al., 2001). This increases the severity of the arid climate, which in turn creates a very difficult environment to carry out agriculture.

Water availability is very low. There is very high reliance on groundwater which is in increasing shortage, evidenced by rapidly falling levels. This is a consequence of the discovery, detection and exploitation of the Kingdom's oil resources from 1938 onwards, which resulted in rapid development and population growth. The ensuing increase in government reserves prompted the Ministry of Agriculture and Water (MAW) since the 1980s to heavily subsidize the sector in order to broaden

the Kingdom's economic base. Although the people of Saudi Arabia have always depended on both shallow and deep aquifers, an explosion in agriculture since the programme began has generated a huge increase in the demand for water to irrigate crops (TED, 2004). Groundwater is currently being exhausted at alarming rates, partly through ill-advised and inefficient use over the last thirty years. Many current patterns of water withdrawal in Saudi Arabia are almost certainly unsustainable, particularly where pumping from aquifers is at rates far greater than recharge. This massive increase in demand for water, especially for irrigation, is reflected in declining groundwater levels in most areas of the country (MAW, 1984). Consequently, Saudi Arabia is facing a growing crisis related to water availability, allocation and policy.

Agriculture in Saudi Arabia is already under pressure from the extreme conditions of the climate and increasing water scarcity and climate change may exacerbate the challenges. The Intergovernmental Panel on Climate Change (IPCC, 2001c) reported that climate change may substantially increase the demand for irrigation water, as changes in atmospheric composition lead to regional and global changes in temperature, rainfall and other climate variables (Saarikko, 1999). The impact of climate change on agriculture, particularly on irrigation water demand, has been a global concern over the last decade, and is a critical issue for arid zones such as the Arabian Peninsula. Many studies have emphasised that climate change will directly impact the quantity and quality of water resources (e.g. IPCC, 2001c). Climate change may also affect crop water requirements (CWR)[1] as they are sensitive to many factors, particularly the prevailing climatic conditions, such as rising temperatures. While future climate change may influence agricultural activity very differently in different parts of the world (Parry et al., 1999); Saudi Arabia may be highly vulnerable because of its almost total dependence on mainly non-

[1] The amount of water required to compensate for the evapotranspiration loss from the cropped field is defined as crop water requirement. Although the values for crop evapotranspiration and crop water requirement are identical, crop water requirement refers to the amount of water that needs to be supplied, while crop evapotranspiration refers to the amount of water that is lost through evapotranspiration (Kassam et al., 2001).

renewable groundwater resources to satisfy the country's industrial, agricultural and domestic needs.

This study examines the potential for future climate change to affect agriculture primarily through its effects on CWR and implications for water use in irrigation. Such impacts could be important for the economic, environmental and agricultural well-being of the Kingdom. The research is done through a focus on the Gassim area of central Saudi Arabia (Figure 1.1).

The following two sections introduce the study area and the context of agriculture in Saudi Arabia: this sets the scene to then introduce the aims of the study.

1.2 The Study Area: Gassim

The area of Gassim lies about 300 km to the north-west of Riyadh, in central Saudi Arabia (Figure 1.1), between latitudes 24° 30' and 27° 15' N, and longitudes 41° 50' and 44° 50' E. The study area is approximately 79,296 km^2 in size (Ministry of Higher Education, 1999) and has a population of 1.5 million (Saudicities, 2004). It lies within an arid zone without renewable surface water, so that the population has had to adapt to extreme climatic conditions. Notwithstanding this deficiency of water the area has always been well-known for its agricultural productivity, and is one of the most important agricultural regions in the country, although it has the same unpromising climate as elsewhere in the Kingdom. This is due to the greater availability of groundwater than in other areas of the country, and the suitability of its soil for cultivation. Therefore, Gassim has become the largest crop production area in terms of output in the Kingdom. Over the last five years, Gassim produced about 27% of the country's wheat, despite representing just 3.5% of the total area of the country. Many farmers and agricultural companies from Gassim successfully market their produce in the global market.

1.3 Agriculture in Saudi Arabia and Gassim

Agricultural activity is concentrated only in areas where groundwater resources are available for irrigation; thus agricultural activity is limited by water availability. Agriculture plays a considerable role in the Saudi economy, employing 569,000 people, or 9.9% of the workforce, and agriculture represents about 7.3% of the Kingdom's GDP (TED, 2004).

Saudi Arabia imported more than 50% of its agricultural needs during the 1970s. After the 1970s oil crisis, the government become keenly aware of the need to lessen this dependence on imports and promote a greater degree of self-sufficiency in certain agricultural products, and to diversify the structure of its economy away from complete oil dependence. Consequently, during the early 1980s Saudi Arabia entered a period of unprecedented growth in terms of agricultural production, particularly for wheat. This expansion in farming was facilitated generously by the government in the form of free land distribution, subsidies (especially for wheat) and interest-free loans (Al-Saleh, 1992). Consequently, the government subsidy to wheat producers in 1993 reached $1.87 billion (us dollar) (TED, 2004). The government has promoted the expansion of agriculture into new lands through subsidies. El-Arnin et al. (2003) indicated that the irrigated area in Saudi Arabia increased from about 0.4 million hectares in 1971 to about 1.62 million hectares in 1992, which represents a 305% increase. Presently most of the country’s food requirements are met by domestic production and surpluses are exported (RESA, 2004). This has been achieved because Saudi Arabia has modernized its agricultural sector, utilizing modern technologies, fertilizers and other new cultivation and production techniques. Nevertheless, agricultural land constitutes only about 2% of the total land area of Saudi Arabia, and wheat represented about 49% of the crop area for the year 2002 (MEP, 2003).

The study area of Gassim represents roughly 28% of the total area of wheat production in the Kingdom. Traditional and commercial modes of farming operate in the study area and these represent the unit of analysis for this study. Traditional farms (TFs) in the Gassim area are generally small, ranging from 5 to 50 hectares and supplied by one well. They are usually surrounded by Tamarisk (Alathel) trees, and located close to the cities and villages, in valleys. TFs are usually managed by one or two labourers often from Bangladesh, India or Egypt. The main farm activities include dates, wheat, vegetable, and livestock production. They also grow alfalfa and several types of vegetables. The farmers in the TFs generally use traditional methods for fertilization, cultivation, harvest and irrigation. Irrigation methods include flood irrigation, which whilst it is the least expensive irrigation method it may be inefficient especially in terms of water use. Furrow irrigation is also used for some crops, such as vegetables. In addition, the TFs use unlined sand canals or sometimes cement-lined canals but rarely use piped canals, because most farmers on the TFs do not use such technology. Furrow irrigation is the most popular method of irrigation in the study area, although it can be inefficient, for example, the irrigation efficiency ranges around 20-40% (Al-Taher, 1987) and yields can be limited. In the TFs wheat is grown in rectangle beds with an area range from 80 to 260 m^2.

The commercial farms (CFs) have existed in the area since the 1980s after the Saudi government began to support wheat production and provide very generous loans and subsidies. The main crops grown in the CFs are wheat and fodder, followed by several types of vegetable grown in greenhouses. Many commercial large-scale farms utilize very modern technology and machinery for fertilization, cultivation, harvesting and irrigation. The CFs use different forms of irrigation methods, including center-pivot, which is expensive but can give good efficiency of water use, and micro-drip irrigation, which is the most expensive technique, but the most efficient at using water. Large guns, and sub-irrigation are also used. CFs farms are generally large, well-managed agricultural businesses, although they are

heavily subsidized by the government. Most CFs are also involved in the production of fodder, milk, poultry, and livestock.

1.3.1 Wheat Production in Saudi Arabia; Water use and Economic Subsidies

Wheat is the most widely produced food crop in the world, and in Saudi Arabia, wheat is considered to be the most important crop in the country. Production in 1970 was about 3000 tons and in 1984 had reached about 1350000 tons (MAW, 1985). By 1984, Saudi Arabia had become self-sufficient in wheat, and was exporting to 30 countries, including China, the former Soviet Union and the nations of the European Economic Community (RESA, 2004). By 1986, production had risen to 2200000 tons and by 1991 had reached 4 million tons. Between 1986 and 1992, Saudi Arabia exported approximately 12 million tons of wheat. The major wheat producing areas are Gassim, Tabuk, and Hail, where average yields reach 8 tons per hectare. The rate and size of the expansion of wheat production in a desert country such as Saudi has surpassed all expectations and enabled the Kingdom to become the world's sixth largest wheat exporter (RESA, 2004, and SAIR, 2004). Figure 1.2 shows the trend in wheat production in Saudi Arabia over the last two decades.

In spite of the difficult climatic conditions the expansion of wheat production has been huge, but this policy has introduced a threat to the country's water reserves. Saudi Arabia uses 80% of its fresh water consumption for agriculture (TED, 2004). The Ministry of Planning (1990) reported that water consumption for growing wheat was estimated at 5.3 billion m^3 (which represented 37% of the agricultural sector’s total water demand in 1987). The implications of these trends for water resources are presented in more detail in Chapter 4.

Incredibly, a loaf of bread weighing only 200 grams requires about 400 liters of fresh water for its production (TED, 2004). Economically, the harvest of 1991/92 was estimated to have cost the government about $ 480/ton, whereas world prices for wheat were $ 100/ton. At present, the national goal is to diversify agricultural production in order to meet the growing demand for other types of crops, and to adjust wheat production to meet local needs (FAO, 1997). Thus, since 1993, in the interests of preserving precious water resources, the production of wheat and other grains has been considerably reduced, and in the last ten years wheat production has been reduced by about 50%, relative to the peak year of 1992 (Figure 1.2). This has been achieved by The MAW.

Saudi Arabia's under-secretary at the MAW in November 1994 stated that subsidies for wheat production had been cut as part of a general policy aimed at diversifying agricultural production in addition to saving water and money. The government subsidy to wheat producers in 1994 fell to $ 850 million, down from $ 1.87 billion in 1993. Accordingly, there has been no surplus wheat for export since the 1996 harvest season. Wheat production in Saudi Arabia is now expected to remain at the level of self-sufficiency (TED, 2004).

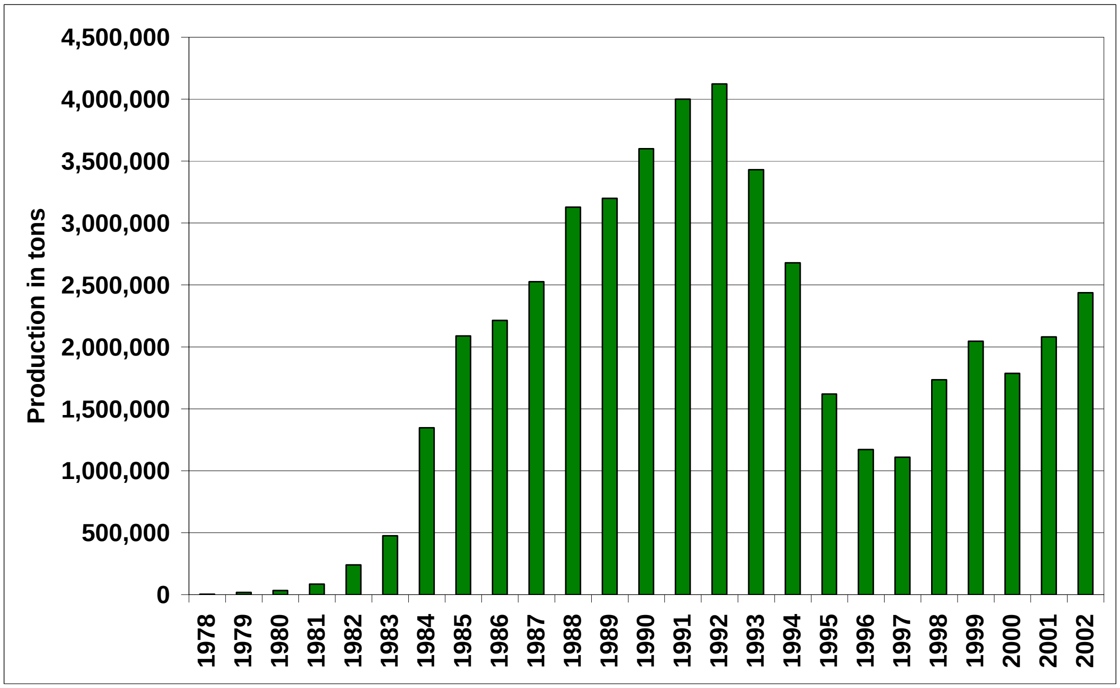


Figure 1.2: Wheat production in Saudi Arabia between 1978 and 2002 (production in tons). (Sources: MAW, 1978-2003).

1.4 Study Aims

The overarching aim of this study is to examine agricultural practices and irrigation water use in Gassim in relation to their sensitivity to climate change. The scientific consensus of the IPCC (IPCC, 2001c) concludes climate change will have effects on temperature, rainfall and evapotranspiration (ET_O), and ultimately on the water demand for irrigation. This study will examine the potential effects of such changes in climate and can be divided into sub-aims as follows.

1. Investigate recent climate variability and groundwater resources in the study area.
2. To examine and compare water use practice in the TFs and the CFs, and evaluate the efficiency of their irrigation water use.

3. Estimate ET_O and CWR of wheat[1] under the actual climate and possible future climates in the Gassim area using General Circulation Models (GCMs) scenarios.
4. Examine the effects of climate change on ET_O, CWR and the length of the wheat growing season (LWGS) in the study area and discuss these changes in relation to other factors affecting decisions about water use in the region (for example, non-climate influences). This includes actions by farmers and managers concerning productivity and adaptation to the impacts of climate change.

This study can be considered as the first integrated study of projected climate change and its consequences for water use in the region. The aim is to contribute to a greater understanding of the climate and water use situation in the study area. In addition, in the face of climate change, it is hoped that this study will have long-term benefits for farming in Gassim, particularly in terms of management of that most precious of Allah's gifts: water. The effects of possible climatic changes on CWR for wheat in Saudi Arabia have not yet been investigated in any detail; only very basic studies have been done as will be shown in Chapter Two. Nevertheless, the effect of climate change on water resources and its consequences for agriculture is an important issue in arid areas such as Gassim. In particular, the CWR of wheat (a major use of water in Saudi Arabia) may increase under climate change, and this could place additional pressures on the groundwater resources upon which agriculture is almost totally dependent. Saudi Arabia at present suffers adverse temperature conditions, which lead to high evaporation rates that impact on agriculture and irrigation, and it is likely that in future the problem will intensify given the current understanding of climate change.

The sensitivity of irrigation water use is examined in two different types of farms: the TFs and the CFs that are representative of typical agriculture in Saudi Arabia. The study is conducted through fieldwork, and is followed by a description of the

[1] The analysis is focused on only one wheat type: winter wheat (*Yecora Rojo*).

procedures for estimating irrigation water requirements for wheat on six TFs using surface irrigation methods, and two CFs using sprinkler irrigation. A study of CWR relative to the current climate is necessary in order to examine existing water use efficiency in the study area. There is no doubt that one of the main challenges facing Gassim is the threat of water shortage and the need to balance the supply and demand for water during the coming decades.

1.5 Thesis Outline

This section provides an outline of the thesis chapter by chapter. Chapter 1 provides an introduction to the main aims of the research, starting with the context of agricultural water use in Saudi Arabia, followed by explanation of the aims. This chapter also introduces the study area, and gives background to agriculture in Saudi Arabia, particularly wheat production.

Chapter 2 reviews important literature relevant to the aims of the research. This includes climate variability, climate change, water resources and water use in agriculture with reference, where possible, to Saudi Arabia. This review is followed in Chapter 3 by explanation of the data and methods used in this thesis. This chapter includes discussion of methods for analysing climate data and water use, and for assessing the impact of climate change on ET_o and CWR. Chapter 4 begins the results and analysis (contained in Chapters 4 to 7) and includes an analysis of observed climate variability and trends for the Gassim area. This analysis is followed by a discussion of recent trends in groundwater levels and abstractions in the study area.

Chapter 5 presents a quantitative evaluation of water use in two types of irrigation system in Gassim; traditional flood irrigation (on TFs) and commercial sprinkler (on CFs). This is followed by an estimation of ET_o and CWR based on the Food and

Agriculture Organization (FAO) approach for the current climate. Comparisons are then made between the FAO-based CWR estimates and measurements of actual water used for irrigation on the farms. Chapter 6 presents climate scenarios using two of the IPCC's SRES emissions scenarios A2 and B2, (IPCC, 2000 see Section 6.3.1 for further explanation) for all of Saudi Arabia and, in greater detail, for Gassim. Two periods are used for the scenarios: the 2020s (2010-2039), and the 2080s (2070-2099). Differences between the two emissions scenarios are highlighted and, for one given emissions scenario, differences between scenarios from three different GCMs, are examined in order to highlight the uncertainties associated with climate change scenarios. The second part of this chapter is concerned with an examination of changes in daily Tmax and Tmin for the recent period 1971-2000, and for the future, using results from the GCM scenarios.

Chapter 7 develops themes from the previous three chapters by discussing the implications of the climate change scenarios for ET_O, CWR, and also the LWGS in the Gassim area. The results are discussed in the context of irrigation water use efficiency and possible adaptation options. Using results from questionnaires with a small number of farmers, the importance of climate change is discussed relative to other concerns. Chapter 8 integrates the key results of the previous chapters and presents the main conclusions, with some discussion of the potential significance of climate change for future agriculture and water use in the region, and possible response in water resources management.

Chapter Two: Literature Review; Climate Change, Impacts on Water Resources and Agriculture with Reference to Saudi Arabia and Gassim.

2.1 Introduction

This chapter reviews the most important books, reports, theses, and papers which are relevant to the main issues in this study, i.e. the current climate of Gassim, potential climate change in the area, and the impact of both on agriculture and water use. Due to the extreme climate, agriculture in Saudi Arabia and in the study area in particular, faces many challenges associated with water availability and supply. The agricultural sector is heavily dependent upon irrigation, and the underground water reserves in some parts of the Kingdom supply almost 100% of the total water consumed. Additionally, over the last 25 years, due to the massive withdrawal of groundwater for the irrigation of popular crops such as wheat, the water table has fallen at an alarmingly high rate; to such an extent that wells have run dry and farms have been abandoned (Al-Saleh, 1992). This study aims to examine these problems in relation to future climate change by assessing water use in irrigation in Gassim under current and future climate conditions. This is conducted in view of the harsh realities of the current climate and increasing pressures on agricultural water use as water availability becomes a critical issue.

In terms of the available literature, just as the study area suffers from a shortage of water, it also suffers from a shortage of research and publications on the agriculture and climate situation in Gassim. Although the issues of climate change and water scarcity may be interrelated, and although these may have a profound impact on the agricultural sector, to date only one theoretical paper has been published in Saudi Arabia pertaining to the effects of climate change on agriculture

and water resources; the important contribution by Alkolibi (2002). No other research has discussed climate change based on the outputs of GCMs in any detail, for Saudi Arabia. This has presented obstacles for the researcher as there are few guidelines, little or no national literature, and therefore no results to guide this study and to compare results with. On the other hand, there have been many studies on climate change and its effects on agriculture; a few including irrigation requirements. Brumbelow et al. (2001) confirmed that various studies have assessed changing irrigation requirements under climate change, and that many more have addressed its effects on water resources throughout the world (see for example the relevant chapters in IPCC, 2001). Some of these have also investigated how increasing temperatures might affect agriculture.

The aim of this chapter is to present a review of the previous research relevant to the research aims. The review therefore discusses research concerning the environmental context of the study area, its current climate, water resources, and agricultural water use. In addition, the review focuses on published research on climate change and its potential effects on agriculture and water use. Finally, this review is used to identify important questions and results relevant to the research objectives.

2.2 Studies of Climate Variability in Saudi Arabia

In terms of the metrological stations established in Saudi Arabia, climatic data and records are limited both spatially and temporally (Al-Swilem, 1999). Climate records in Saudi Arabia only started with the search for oil, and so the first station in the country was established in Dhahran on the eastern cost of Saudi Arabia in 1935 (Ministry of Higher Education, 1999). Subsequently, Ras Tanura station was established in 1948 in the same region by the Arabian Oil Company (Aramco). In the beginning of the 1950s many stations were established in the country's airports (Ministry of Higher Education, 1999), and by 1988, there were 63 climate

stations in Saudi Arabia, covering around 2.25 million km^2 (Al-Swilem, 1999). In the study area, Unizah weather station was established in 1964.

Saudi Arabia is an arid region, except for the south-western part of the country, which is classified as semi-arid according to the Köppen Classification. Maximum summer temperatures often exceed 45°C with very low relative humidity and clear skies most of the time (Alkolibi, 2002). The annual evaporation rate in most of the country, except for the south-western mountain area, is more than 1200 mm (Aljarash, 1989). Algshuan (1990) studied Class A pan evaporation for the study area and found it to range from 79 to 275 mm/month in December and June, respectively.

Concerning rainfall, Al-Saleh (1994) asserted that rainfall intensity in Saudi Arabia is generally high, with about 50% of rainfall at over 20 mm/hour, and about 20-30% higher than 40 mm/hour. The average annual rainfall in Saudi Arabia ranges from 80 to 140 mm, but in the mountainous south-western part of the country it reaches 600 mm (Ministry of Higher Education, 1999). In the study area, the total annual rainfall has been estimated at 130 mm/year over 1964 to 1989 (Almogaoud, 1993), and Almisnid (1999) estimated it at 89 mm/year over 1973 to 1993. In addition, Almogaoud (1993) noted that July and August is an almost rainless period, whereas spring is the wettest season.

In terms of recent trends in the observed climate, Alkolibi (2002) investigated temperature and rainfall at four stations in Saudi Arabia (Riyadh, Jeddah, Almadinah and Dhahran) over a 37-year period (1961-1997). He concluded that there had been no clear increase in temperature at the stations (linear trend R^2 = 0.34, -0.07, 0.05 and 0.01, respectively). In terms of the total annual rainfall at the four stations, he concluded that the records for Jeddah and Riyadh did not show any sign of change, but that there was evidence of increased rainfall in Dhahran and Almadinah, (R^2 = 0.15 and 0.14, respectively; F value for significance = 0.02 for both stations, and for the Riyadh and Jeddah stations R^2 = -0.01). Qureshi

(1994) studied the average annual temperatures at Riyadh and found an increase of 1.2°C over a 26-year period (1966-1991). He supported this with observations from another station near Riyadh Airport which showed a 0.63°C increase for the same period. He also identified changes in average annual temperatures for other stations widely distributed in the interior of the country, and found increases ranging from 0.1°C in Tabuk to 1.4°C in Sakaka, while in the study area of Gassim he found it to be 0.8°C.

The study area is characterized by very hot, dry days in summer (May to October), when temperatures can reach 50°C, while the winter days are mainly cool and dry with very low night-time temperatures, which can cause freezing. Because of the aridity, and hence the relatively cloudless skies, there are great extremes of temperature, but there are also wide variations between the seasons (FAO, 1997). Air temperature follows a regular seasonal trend, with a minimum in January and a maximum in July. Almogaoud (1993) estimated the annual average temperature of the study area at 24°C (1964-1989), while the annual range was 21.3°C. Alwaseedy (1996), over 1970 to 1991 found the average monthly temperature to range from 19.4° to 42.5°C in January and July, respectively. He also asserted that the absolute Tmax had been recorded in the study area of Gassim at 50.2°C in July 1987, and the absolute Tmin (-4.5°C) in both January and February of 1989.

In terms of aridity, UNESCO (1979) identified an aridity index that can be used to measure the extent of dryness, and De Pauw (2002) employed this index, based on the ratio of annual rainfall to annual ET_O, and found the study area to be arid. Almogaoud (1993) estimated aridity using the Johansson Index (1951) and the results showed that Gassim is in the Arid Class 60%. The main reasons for the region's aridity are its remoteness in relation to the major rain bearing weather systems, such as the North Atlantic depressions and the Indian monsoon, and its exposure to air predominantly continental in origin (De Pauw, 2000). The aridity

reflects the negative balance between very low water supply from rainfall and very high evaporative demand of the atmosphere.

2.3 Future Climate Change

2.3.1 Temperature Change

Over the last 100 years humans have begun to have a discernible influence on the Earth's climate, causing it to warm (IPCC, 1996a, 1998, 2001c) such that in 2001 IPCC (2001a) stated that there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities. According to the latest observations of temperature, the 20th century warming trend is continuing (Met Office, 2003). In addition, the UK Meteorological Office (2003) pointed out that the projections of future climate suggest that without substantial mitigation, further large-scale changes in climate will occur. Combustion of fossil fuels could, by 2050, result in a doubling of atmospheric CO_2, and a rise in global average surface temperatures by 1.4° to 5.8°C over the period 1990 to 2100 based on a range of emission scenarios and a number of climate models (Ruttan, 2001 and IPCC, 2001a).

IPCC (2001a, p.527) summarised temperature changes for two future periods centred on the 2035s and 2080s. They used an Atmosphere-Ocean General Circulation Model (AOGCM, also shortened to GCM) and the average change and range in global average surface air temperatures with respect to 1961 to 1990. It should be emphasized that projections of climate for the next 100 years have a large range due both to the differences of model responses and the range of Greenhouse Gas (GHG) emission scenarios (Table 2.1 and Figure 2.1). IPCC (2001a), based on the above findings, also reported that globally, with an increase in the average surface air temperatures, there will be more frequent extremely

high maximum temperatures and less frequent extremely low minimum temperatures. There is expected to be a decrease in the diurnal temperature range in many areas, with night-time lows increasing more than daytime highs.

Scenario		**2021 to 2050**	**2071 to 2100**
A2	Average	+1.1°C	+3.0°C
	Range	+0.5 to +1.4°C	+1.3 to +4.5°C
B2	Average	+1.2°C	+2.2°C
	Range	+0.5 to +1.7°C	+0.9 to +3.4°C

Table 2.1: Summary of the average change and range in global average surface air temperatures from the 1961 to 1990 average, to the 2035s and the 2080s, for the AOGCM experiments with two GHG emission scenarios. All changes are calculated with respect to the 1961-1990 average. (The two emissions scenarios are discussed in Chapter 6 as they the basis of the change scenarios used in this study).

Focusing on Asia, where Saudi Arabia is located, IPCC (2001c) pointed out that the climate of arid Asia is of the warm temperate type, with hot, dry summers. The highest values for DTR (in the order of 20°C) are experienced in this region. Moreover, an average Tmax of >45°C in July is not uncommon in some parts of arid Asia, and in most of the Middle East. In terms of future climate change, IPCC (2001c) reported that GCMs suggest an area-averaged annual average warming of about 3°C and 5°C by the 2050s and 2080s, respectively, over the land regions of Asia; largely because of future increases in atmospheric concentrations of GHGs. However, reporting in more detail on Asia, IPCC (2001c) also suggested that projected warming would be higher during the Northern Hemisphere winter than during the summer. The GCM simulations projected relatively more pronounced increases in Tmin than in Tmax on an annual average basis during winter, and hence a decrease in the DTR. During summer, however, an increase in DTR is projected, suggesting that the Tmax would have more pronounced increases relative to the Tmin (IPCC, 2001c).

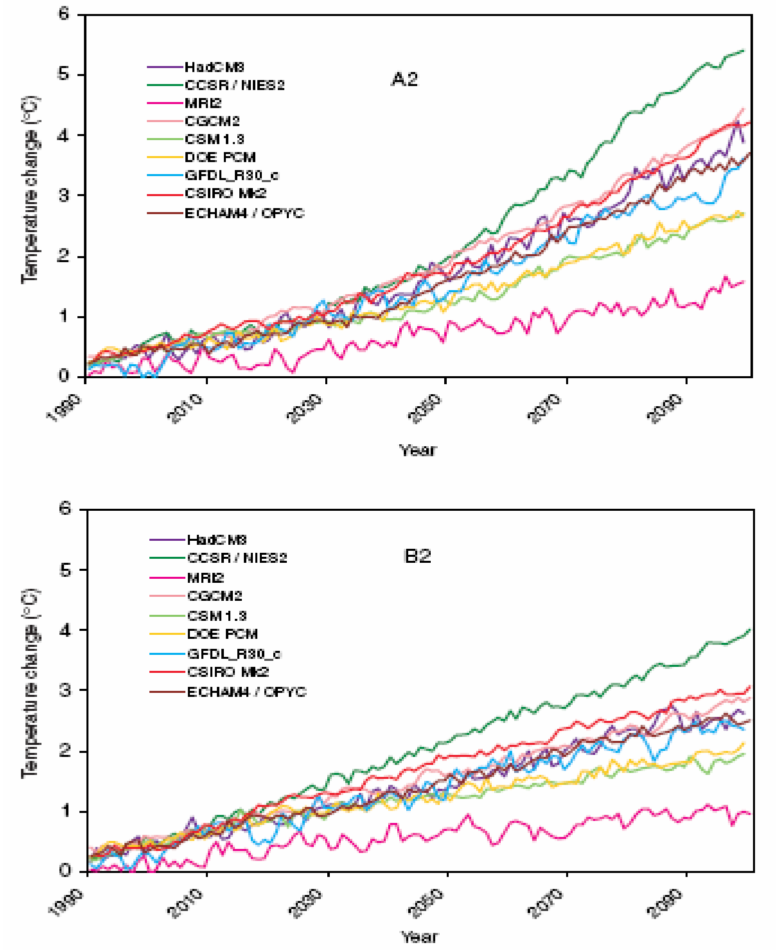


Figure 2.1: The time evolution of the globally averaged temperature changes relative to the 1961-1990 average for different GHG emissions scenarios A2 (top) and B2 (bottom) (Source: IPCC, 2001a, p 542). The plots highlight differences between AOGCMS and emissions scenarios.

In terms of Saudi Arabia, Alkolibi (2002) found that GCM scenarios indicate that the tropical deserts, including Saudi Arabia, will experience an increase in temperature and a decrease in rainfall, and that the variability of both will increase. These results may not hold for a more recent set of GCMs studies as presented here in Chapter 6.

2.3.2 Rainfall Change

In contrast to the generally high level of agreement between scenarios for increasing temperatures, there are greater discrepancies between GCMs for scenarios of rainfall. Kabat et al. (2002) stated that rainfall change is more variable than temperature change. Many studies have ascertained that there remains a high degree of uncertainty in terms of projected rainfall, for example, Parry (1990) emphasized this noting that not only in its quantity but also its distribution over time and space and even the direction of change. Reilly (2004) also determined that climate scientists have little confidence in climate model projections for rainfall changes. Therefore, confidence in recent results awaits more study and use of a wider range of climate model scenarios. Kabat et al. (2002) clarified the sources of the uncertainties in the projected rainfall as being for two primary reasons: firstly, rainfall is a secondary process in GCMs, and secondly, rainfall is poorly represented as heavy rainfall systems frequently occur on scales that are considerably smaller than the typical grid scale of GCMs at 2-3° latitude/longitude.

Nevertheless, IPCC (2001a) indicated that the average rainfall response using the SRES A2 forcing, for the 30-year average 2071 to 2100 compared with 1961 to 1990, is an increase of 3.9% with a range of 1.3 to 6.8%, while using the SRES B2 scenario it amounts to an increase of 3.3% with a range of 1.2 to 6.1% (Table 2.2). The lower rainfall increase values for the B2 scenario are consistent with less globally averaged warming for that scenario at the end of the 21st century compared with A2 (higher GHG emissions). Figure 2.2 shows the time evolution of the globally averaged rainfall change relative to the years 1961 - 1990 for the SRES simulations A2 and B2.

Globally, IPCC (2001a, p.527), based on findings from the models analysed, reported that:

- The globally averaged mean water vapour, evaporation and rainfall will increase.

- Most tropical areas will have increased average rainfall, most of the sub-tropical areas will have decreased average rainfall, and in the high latitudes the average rainfall will increase.
- The intensity of rainfall events will increase.
- Rainfall extremes will increase more than the averages will and the return periods for extreme rainfall events will decrease almost everywhere.

Scenario		**2021 to 2050**	**2071 to 2100**
A2	Average	1.2%	3.9%
	Range		1.3 to 6.8%
B2	Average	1.6%	3.3%
	Range		1.2 to 6.1%.

Table 2.2: Summary of the average change and range in global average rainfall, from the 1961 to 1990 average to the 2035s and the 2080s, for AOGCM experiments with two GHG emission scenarios (A2 and B2). All changes are calculated with respect to the 1961-1990 average.

For Asia, the GCMs summarised by IPCC project that annual average rainfall will increase by approximately 7% and 11%, by the 2050s and 2080s, respectively, over the land areas (IPCC, 2001c). Despite this, Alkolibi (2002) asserted that GCMs suggest a lower likelihood of rainfall over the Mediterranean and North Africa, including Saudi Arabia.

Arnell (2004) found that annual rainfall from the Hadley Centre GCM HadCM3 decreases around the Middle East. Therefore, and because of a decrease in total rainfall, the frequency and severity of droughts might increase, as well as more frequent dry spells and greater ET_o (Frederick et al., 1999). In addition, IPCC (1996a and 1996b) stated that the frequency and harshness of droughts may increase in some areas as result of a decrease in total rainfall, more frequent dry spells, and greater ET_o.

IPCC (2001c) emphasises that rainfall is the main driver of variability in the water balance over space and time, and changes in rainfall have very important

implications for hydrology and water resources. As all GCMs project rising temperatures, this will most probably engender increasingly severe water-stress conditions in the region, and therefore, degradation of existing vegetation patterns in the study area is quite possible with rises in surface air temperature and depletion of soil moisture. The combination of higher temperatures and ET_O and the possibility decreasing rainfall could put Saudi Arabian agriculture in an even more vulnerable position than its present situation (discussed in Chapter 4).

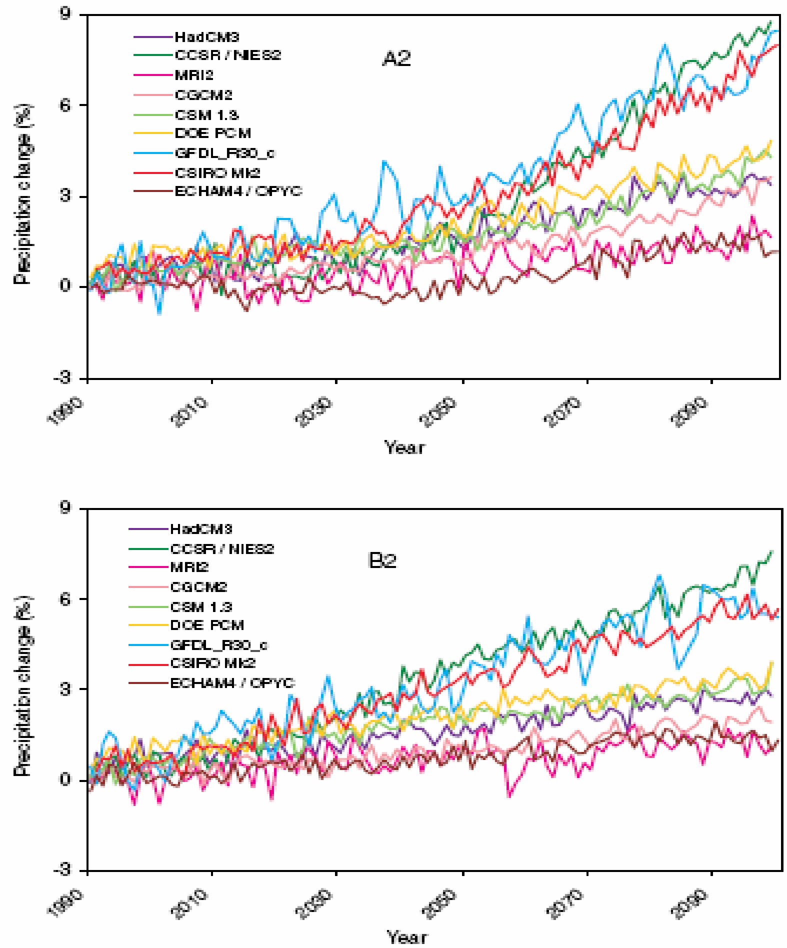


Figure 2.2: The time evolution of the globally averaged rainfall change relative to the years 1961 - 1990 for the SRES simulations A2 (top) and B2 (bottom) (Source: IPCC, 2001a, p. 542).

2.3.3 The Direct Effects of CO_2 on Plants

Much of the concern about rising CO_2 levels is about its effects on climate, but rising CO_2 levels will also have direct effects on plant growth, for example Rosenzweig et al. (1998) confirmed that both climate change and atmospheric CO_2 may impact on crop production. Moreover, Frederick et al. (1997) reported that increasing atmospheric GHG enrichment has been observed since pre-industrial times, tending to warm the surface and producing other climate changes. They stated that the most important of these gases are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), which have increased by about 30%, 145%, and 15%, respectively, over the last 250 years.

Parry (1990) stated that there are three ways in which climate change due to GHGs may be important for agriculture. Firstly, CO_2 has a direct effect on the growth rate of plants, i.e. elevated CO_2 levels increase plant photosynthesis and thus crop yields. Reilly (2004), and also Downing et al. (2003) highlighted that changes in atmospheric CO_2 levels have a direct impact on plant physiology, affecting how they grow and how much water they transpire. Secondly, changes in CO_2 induce changes in climate, which may alter temperature, rainfall and other climate variables, and these may influence plant productivity. Finally, rises in sea levels caused by climate change may lead to loss of farmland by inundation and increasing salinity of groundwater in coastal areas.

Rosenzweig et al. (1995) clarified the relationship between CO_2 and plants as follows

> *''CO_2 enters a plant through its leaves. Greater atmospheric concentrations tend to increase the difference in partial pressure between the air outside and inside the plant leaves, and as a result more CO_2 is absorbed and converted to carbohydrates.''* (Page number not given)

Generally, the effect of increasing atmospheric CO_2 on crops is to increase crop yield (Olesen, 2001); by increasing plant photosynthesis (Reilly, 2004), plants use less water (Drake, 1999) and there is improved water use efficiency (Morison and Gifford, 1984). For example, controlled environment experiments indicate that elevated CO_2 concentrations increase the resistance of plant stomata to water vapor transport, resulting in decreased transpiration per unit of leaf area (Frederick et al., 1997). As Drake et al. (1997) and Rosenzweig et al. (1995) also explained, stomatal conductance is decreased under elevated CO_2, inducing plants to close their stomata, through which CO_2 is absorbed and water vapor is released. Therefore, with CO_2 enrichment crops may use less water even while they produce more carbohydrates. This dual effect may improve water use efficiency, which is the ratio between crop biomass and the amount of water consumed. Responses, however, depend on crop species, as plant species vary in their response to CO_2 in part because of differing photosynthetic mechanisms (Fischer et al., 2002). Additionally, Arnell (1996) pointed out that increasing atmospheric CO_2 may cause changes in plant physiology firstly by changing the stomatal conductance of some plants resulting from the reduction in transpiration. Secondly, some plants grow more vigorously in a CO_2-rich environment, with effects depending on how the plant actually absorbs CO_2.

Rosenzweig et al. (1995) indicated that crop species vary in their response to CO_2 according to their physiological class; wheat belongs to the class of C3 plants which responds readily to increased CO_2 levels. Parry (1990) indicated that a doubling of atmospheric CO_2 enrichment from 330 to 660 parts per million would cause a decrease in stomatal aperture by 40% in both C3 and C4 plants, and that this might reduce transpiration by 23 to 46%, causing an increase in the growth and yield of C3 crops (such as wheat, soybean and rice) by between 10 and 50%. Frederick et al. (1997) cited some experiments suggesting that a doubling of CO_2 will increase stomatal resistance and reduce transpiration by about 50% on average. Moreover, Downing et al. (2003) stated that the effect of CO_2 alone may decrease water demand for irrigation by around 5 to 10% in the 2020s and by 15

to 20% in the 2050s. Gleick et al. (2000) also highlighted that some laboratory and field studies have shown that certain plants will decrease their water use when exposed to higher CO_2 levels. However, some studies suggest that much of this improvement would be lost if increased leaf area offset increased water-use efficiency (Field et al. 1995, Korner 1996, Rötter and Van De Pauw Geijn 1999). Downing et al. (2000) investigated the relationship between water use efficiency and increasing CO_2, and noted that water use efficiency in wheat increased by 50-60% for a doubling of current CO_2 concentration.

This study does not directly incorporate the effects of increasing concentrations of atmospheric CO_2 enrichment on stomatal conductance. This is partly because the processes are too complex and the experimental evidence is noisy, and as described above, there is no clear signal. CO_2 effects could be influenced by all sorts of factors, such as soil type and uncertainty about future CO_2 levels (Downing et al., 2003). It is often difficult to transfer results derived from greenhouse studies into the real world where many other factors might be involved such as soil, climate, solar radiation, pests, diseases, and weeds. In the same context Arnell, (1996) pointed out that the responses of plants to elevated atmospheric CO_2 levels may be affected by climate or the availability of nutrients, and plants may adapt to altered CO_2 concentrations. IPCC (2001c) cited that some model studies (e.g., Field et al., 1995, for forests; Bunce et al., 1997, for alfalfa and grass; Cao and Woodward, 1998, on the global scale) suggest that the net direct effect of increased CO_2 concentrations on the catchment scale will be small.

Therefore, many studies assume no change in stomatal conductance for the above reasons in accordance with the IPCC (2001c) report that states that there is clearly a large degree of uncertainty over the effects of CO_2 enrichment on catchment-scale evaporation. It is apparent that many of the reported effects of increased atmospheric CO_2 on plant physiology are inconsistent, and that this may be the result of different experimental conditions and objectives (Downing et al.,

2003). Slafer et al. (1997) reported that to the best of their knowledge, there are no studies of wheat under long-term exposures to different CO_2 levels which investigate developmental processes such as the timing of critical development stages, the rates of leaf primordia initiation, and the rates of leaf appearance.

2.3.4 Evapotranspiration (ET_O)

ET_O is defined by Kassam and Smith (2001, p.2) as:

> *"ET_O is the evapotranspiration from a reference crop with the specific characteristics of grass, fully covering the soil and not short of water and represents the evaporative demand of the atmosphere at a specific location and the time of the year independently of crop type, crop development and management practices, and soil factors. The only factors affecting ET_O are climatic parameters. Consequently, ET_O is a climatic parameter and can be computed from weather data."*

Estimating ET_O is very important in order to evaluate CWR for crop management and irrigation scheduling. ET_O therefore plays an important role in irrigation design and management as it determines the intervals between irrigation applications (Southorn, 1997). Seasonal ET_O is affected by crop characteristics, climate, length of growing season, time of planting, soil moisture levels and agricultural practices (Doorenbos and Pruitt, 1977).

A large number of empirical equations for calculating ET_O are proffered in the literature, some of which are soundly based on an impressive range of field data. These include the temperature based methods, such as Thornthwaite (1948), and Blaney and Criddle (1950); radiation methods, such as Hargreaves (1956), and Turc (1961); and finally, combination methods such as Jensen and Haise (1963),

Penman (1948), Rijtema (1965, 1969), Priestley and Taylor (1972) (Saeed, 1988). When estimating a reference crop ET_O, Jacobs (2001) reported that there are three general approaches to consider: temperature methods, radiation methods and combination methods. The combination methods are based on the original Penman (1948) combination equation, and these require more data than temperature or radiation methods such as Thornthwaite and Turc, respectively, as the combination methods include sunshine duration, wind speed and relative humidity with air temperature.

The Penman-Monteith combination method is recommended by the FAO as the international standard (Allen et al., 1998). In the same context, Ventura et al. (1999) pointed out that this equation is also recommended by the World Meteorological Organization (WMO), and it is used in the FAO CROPWAT irrigation scheduling software (Smith 1993). Droogers et al. (2002) reported that of the many existing ET_O equations, the FAO-56 application of the Penman-Monteith equation (Allen et al., 1998) is currently widely used and can be considered as a standard.

In this study, the FAO Penman-Monteith combination method is used. Jacobs (2001) pointed out that investigators throughout the United States and in many countries have demonstrated that this method is preferable to radiation or temperature-based methods for assessing reference ET_O. Restrepo et al. (1995) found that Penman-Monteith was reliable and accurate in their study in the South Florida region, and they recommended this method to the South Florida Water Management District. In addition, Elagib (2002) pointed out that the FAO Penman-Monteith is more accurate and provides more reliable estimates for ET_O than the temperature-based method of Thornthwaite. Droogers et al. (2002) stated that FAO Penman-Monteith equation has three advantages over many other methods. Firstly, the method can be used globally without any need for additional parameter estimations as it is a physically based approach. Secondly, the method is well

documented, and is implemented a wide range of software. Thirdly it has been tested using a variety of lysimeters which have shown that, in most cases, it is the best method for estimating ET_o. DehghaniSanij et al. (2004) assessed the estimates of ET_o obtained from six methods (Penman, Penman–Monteith, Wright–Penman, Blaney–Criddle, Radiation balance, and Hargreaves) against experimentally determined values in a semi-arid environment, Karaj in Iran. They found that Penman–Monteith produced the most reliable estimates (compared to lysimeter results) for the region.

For semi-arid and arid conditions, Fawzi et al. (1992) showed how Penman was more realistic than the Jensen-Haise (Jensen, 1973) method for estimating the actual crop water needs. Al-Amri (1994) mentioned that Penman was the most accurate method and most closely corresponded to the local results of the NADEC[1] Company's calculations in Saudi Arabia. This is also supported by Mohammad (1998) in field experiments in Riyadh. He estimated ET_o using ten well-known equations with climatic data obtained in Saudi Arabia, and compared the results with the measured evaporation from a class A pan. The best correlation was obtained with the Penman method (R^2 0.72), and Thornthwaite showed the poorest correlation (R^2 0.26).

In terms of future climate change and ET_o Martin et al. (1989) found that the effect of higher temperatures on ET_o may be either moderated or exacerbated by changes in the other climatic elements (radiation, humidity, wind) and in plant factors (leaf area index, stomatal resistance). In addition, McKenney et al. (1993) pointed out that changes in climatic elements other than temperature are likely and these could have important impacts on ET_o. They estimated the sensitivity of ET_o

[1] NADEC is one of the largest agricultural companies in Saudi Arabia, and was established in 1981. It was also the first Saudi share stock company, and its farms specialise in milk production and calf fattening [25,000 heads]. It has projects with a total cultivated area of 40,000 hectares. (http://www.mirnah.com/client3.html).

to climate change using eight alternative ET_O estimation methods. The simulations were performed using climate data from five sites in the North American Great Plains. The results indicated that the eight methods differ, in some cases significantly, in their sensitivitiy to temperature and other climate inputs. Two GCM-derived scenarios of climate change the predicted response of ET_O varied in magnitude, and in some cases in sign, according to the estimation method used. For southern England, Arnell (1996) estimated the sensitivity of ET_O to changes in temperature, and found that it depends very much on the formula used. For example, the Thornthwaite and Blaney-Criddle formulae tend to produce a higher change in ET_O than Penman. For a 4°C increase in temperature, ET_O increased by 9% - 23% (Penman), 15% - 50% (Thornthwaite) and 31% - 61% (Blaney-Criddle). Differences between methods can be attributed to differences in their sensitivities to given changes in climate, and differences in the climatic factors they consider.

In relation to increases in temperature, Parry (1990) warned that even the relatively small increases of about 1.5°C projected for lower latitudes under a doubling of GHG, ET_O rates would increase by as much as 5% to 15%, and this, if there were no compensating increases in rainfall, would tend to reduce yields. He suggested that at mid-latitudes, evaporation increases by about 5% for each degree of average annual warming (Parry, 1990). Arnell, (1996) noted that when air temperature increases, air can hold a greater amount of water vapour, by between 5% and 6% more, per °C. In paddy fields in southern Taiwan, Yu et al. (2002) estimated that ET_O may increase by approximately 28 mm and 25 mm (5.5% and 3.2%) for the first and second crop season, respectively, based on the increases in temperature with various GCMs (2°C and 3°C, respectively). Gleick et al. (2000) pointed out that the Hadley Center for Climate Prediction GCM HadCM2 has consistently projected that global average evaporation might increase in the range of 3% to 15% for an equivalent doubling of atmospheric CO_2 concentration.

2.3.5 Climate Change, Agriculture and Irrigation

IPCC (2001c) states that:

> *''The water and agriculture sectors are likely to be most sensitive to climate change-induced impacts in Asia.''* (p.515). Downing et al. (2003, p.xviii) also highlighted the interaction between climate, agriculture and water: *''climate change could affect irrigation water use via changes in plant physiology, altered soil water balances, cropping mixes, and cropping patterns.''*

Globally, there have been many studies of the effects of climate change on agriculture with some reference to water resources, and there is a general concern that changes in the climate may have negative impacts on ET_O, CWR, and water resources. Frederick et al., (1999) stated that scientific research shows that climate change will have significant impacts on temperature, rainfall, ET_O and runoff, and in the end, on the nation's water supply. Downing et al. (2003) pointed out that climate change may influence crop yield and irrigation water demand through changes in local weather, particularly rainfall and ET_O. Furthermore, Reilly (2004) postulated that the climate could have far reaching ramifications for every aspect of agriculture, including the production of crops, livestock, transportation of agricultural products, and their marketing.

Parry et al. (1999) note that in different parts of the world climate change is expected to affect agriculture in very different ways, and this view is supported by IPCC (2001c), which concluded that climate change will impact on the agricultural sector by causing both costs and benefits on scales ranging from individual plants or animals to global trade networks. Nevertheless, the general consensus is that the impact of climatic change will be negative in most regions of the globe (Hartig et al., 1997). IPCC (2001c) states that climate change constitutes an additional

pressure that could change or endanger ecosystems and the many goods and services they provide that depend on them.

Rosenzweig et al. (1995) suggested that rising temperatures might extend the length of the potential growing season, allowing earlier planting of crops in the spring, which could lead to earlier maturation and harvesting, and possibly to two cropping cycles in one season (although faster maturation may decrease yield). On the other hand, in middle latitudes, such as Saudi Arabia, higher temperatures may decrease the length of the potential growing season, in fact most of the crops in the study area of Gassim are grown just within their limits of maximum temperature tolerance. Downing et al. (2003) highlighted that changes in temperature may alter where each crop can be best grown. The effect of warmer temperatures on ET_O, together with the possibility of lower rainfall, will also be important. Rosenzweig et al. (1995) underlined that increased occurrence of moisture stress during flowering, pollination, and grain-filling is harmful to most crops and particularly to wheat.

The potential effects of climate change on water availability is widely recognised, for example, IPCC (2001c) expects an intensification of the global hydrological cycle, causing major impacts on regional water resources, affecting both ground and surface water supplies for irrigation. It continued that changes in the total amount of rainfall, and in its frequency and intensity, could directly affect the timing and magnitude of floods and droughts, shift runoff regimes, and alter groundwater recharge characteristics. As a direct consequence, these changes may influence both rainfed and irrigated crop yields and CWR for irrigation (Chen et al., 2001). Therefore, climate change is expected to have a major impact on water resources (Kabat et al., 2002). Rosenzweig et al. (1995) stated that peak irrigation demands are projected to rise due to the expected increase in the frequency of severe heat waves.

There have been some specific studies of climate change and irrigation. For example, Brumbelow et al. (2001) assessed irrigation needs for the United States under potential climate changes, using the Canadian Center for Climate Modeling and Analysis GCM (CGCM1). They found greater irrigation demands in the southern United States and decreased irrigation demands in the northern and western United States. Another study by Rosenzweig et al. (1995) suggested that the demand for water for irrigation is projected to rise in a warmer climate, which may make the practice of irrigation more expensive as groundwater levels fall and the energy needed to pump water increases.

More recently, Downing et al. (2003) reported that climate change could affect irrigation water use and from a survey of irrigation of outdoor crops in the UK in 2001 they confirmed that water use for irrigation is currently growing at 2%-3% each year although much of this trend is due to non-climate influences. For the future, Parry (1990) concluded that increases in the need for and the costs of irrigation may occur in order to substitute for moisture losses due to increased ET_O. Chen et al. (2001, p.7) in a study of effects of climatic change on a water dependent regional economy in the Texas Edwards aquifer found that;

> *''In terms of agriculture, climate change moves water away from agriculture and adds to costs through higher pump lifts and irrigation requirements with lower yields causing a reduction in farm income ranging from 16-30% in 2030 and 30-45% in 2090.''*

Another example of the negative effects of climate change was reported by Arnell (1996) who simulated the behaviour of a hypothetical irrigation system in Lesotho, examining changes in both demand and supply. He found substantial changes in the reliability of the irrigation system, where an increase in temperature of 2°C, for example, could increase demand for irrigation water by over 20%. Chen et al. (2001) in Texas, using HadCM2 and Blaney-Criddle obtained a decrease in crop and vegetable yields and an increase in CWR. For example, for 2090, the irrigated

corn yield decreased by 3.5% whereas the irrigation water requirement increased by 31.3%.

Potential increases in demand for irrigation water due to climate change will have implications for regions experiencing water scarcity. IPCC (2001c) pointed out that global water withdrawals are already estimated to increase by 23-49% by 2025 over 1995 values. Cosgrove et al. (2000) concurred that by 2025 water use may increase by as much as 25-50% on the global scale. The greatest rates are projected for developing countries, e.g. in Africa and the Middle East, even without taking climate change into account. In the same context, Kabat et al. (2002) confirmed that even without climate change, most developing countries will be confronted with serious water problems by the middle of the 21st century.

In terms of Asia, where Saudi Arabia is located, IPCC (2001c) reported that based on present scientific research, certain specific risks are linked to climate change in relation to agriculture and water:

- There is a potential for drier conditions in arid and semi-arid Asia during summer, which could lead to more severe droughts.
- Freshwater availability is expected to be highly vulnerable to anticipated climate change.
- Crop production may be threatened by a combination of thermal and water stresses.

In Egypt, Eid and his collaborators (Eid and El-Sergany 1993; Eid et al., 1993, 1995) estimated that climate change may decrease the national production of all crops; they found decreases ranging from 11% for barley to 28% for soybeans, including 18% for wheat, in relation to a 16% increase in the CWR. Also in Egypt, simulated studies showed dramatic decreases in yields for wheat and maize at four sites along the Nile by the 2050s (El-Shaer et al., 1997). Egypt is a neighbour of Saudi Arabia and, as Rosenzweig et al. (2002) pointed out, is particularly vulnerable to climate change because of its dependence on the River Nile. Hillel

and Rosenzweig (1998) noted that exacerbated drought stress might occur, particularly in the semi-arid tropics and subtropics because of an increase in ET_O. Also, Elagib (2002) found that climate change might have a large enough effect on ET_O regimes to cause an intensification of agricultural droughts over five different climate zones in Sudan. The areas most vulnerable to climatic change are those tropical and subtropical deserts and semi-arid regions that already suffer adverse climatic conditions, such as Saudi Arabia. Any rise in temperature or reduction in rainfall, along with increases in the variability of these factors, will exacerbate the existing challenges of the climate in these areas (Alkolibi, 2002).

Although no climate impact studies exist specifically for Saudi Arabia it is possible to use regional or country scale results from global impacts studies. Parry et al. (1997) estimated changes in national grain crop yields based on simulations using various crop models and climate change scenarios at 82 sites. The results predict negative cereal yields in Saudi Arabia by the 2020s (10%), 2050s (20%) and the 2080s (20-30%) due to the negative effects of temperature stress. With GCM scenarios from HadCM2 and HadCM3 Parry et al. (1999) found potential changes in Saudi Arabian cereal yields to be detrimental, ranging from 0 and -2.5% for the 2020s and 2050s compared with 1990, and by the 2080s ranging from -2.5 to -5%. They pointed out that these decreases in potential crop yields are likely to be caused by a shortening of the crop growing period, by decreases in water availability due to higher rates of ET_O, and by poor vernalization of temperate cereal crops. Parry et al. (2004) also analysed the global impacts on wheat, rice, maize, and soybean production for the 2020s, 2050s and 2080s (compared with 1990) under the HadCM3 and SRES emission scenarios, with and without CO_2 effects. The results for Saudi Arabia indicated decreases, with expected losses in national cereal yields 2.5% (2020s), 2.5% (2050s) and 30% (2080s) compared with 1990.

2.3.6 Crop Physiological Effects of Temperature Extremes

Global climate change is likely to result in increases in both average temperatures and the frequency of periods with extremely high temperatures (Wollenweber et al., 2002). It has already been noted that many crops in Saudi Arabia already grow near their thermal limits and therefore more frequent and hotter temperature extremes may have negative effects on crop yields. Amir (2001) surmised that heat stress is a common constraint during the anthesis and grain filling stages in many temperate environments in South and West Asia, including the study area. Even though in Saudi Arabia wheat is grown as a winter season crop the relatively high temperatures that occur during the growth cycle, especially at the end of the growing season, already put it at risk. Extremes of temperature have broad and far-reaching consequences for agricultural production. Adams (1997) identified the various agricultural sectors most affected by extreme heat as livestock, crops and water resources.

The effects of extreme temperatures on wheat are the focus of this subsection. There is a negative effect on yields through increased temperatures because of accelerated rates of development (Slafer et al., 1997). Moot et al. (1996) indicated that temperate crop yields tend to increase with enhanced CO_2 concentrations, but that this may be offset by the negative effects of warmer temperatures. Amir et al. (2001) pointed out that heat stress is an important inhibitor in wheat production, affecting many biological activities in the cell membranes. However, field studies in wheat, considering increases in both CO_2 and temperature, suggest that this interaction could result in either unchanged or decreased yields, depending principally on the actual temperature reached (Slafer et al., 1997). More specifically, high temperatures (>31°C) imposed on wheat after anthesis can decrease the rate of grain-flling (Stone et al., 1995), whilst high temperatures imposed before anthesis can also decrease yield (Ferris et al., 1998). Ferris et al. (1998) also reported that grain set is reduced by temperatures warmer than 30°C during the period from the onset of meiosis in the male generative tissue to the

completion of anthesis. It can be concluded that in all cases, the negative effect of higher temperatures on wheat yield is due to faster development which leads to shortened periods for radiation interception and organ formation.

2.4 Water Resources in Saudi Arabia

Saudi Arabia has no perennial lakes or rivers and there is almost no surface water except for a few reservoirs that are dry for most of the year. Furthermore, the runoff rate in the country is one of the lowest in the world (Sagga, 1998). Surface water resources have been estimated at about 2.2 km^3/year, most of which percolates to recharge groundwater; with about 1 km^3 recharging usable aquifers. The total (including fossil) groundwater reserves have been estimated at about 500 km^3, of which 340 km^3 are probably abstractable at an acceptable cost in view of the economic conditions of the country (FAO, 1997).

In Saudi Arabia many aquifers suffer high rates of depletion and severe drops in ground water levels have been observed because of overuse in agriculture (Alkolibi, 2002). For instance, between 1984 and 1990, the ground water level of the Manjur aquifer, which also supplies the capital and many other urban areas, has dropped 10.8 m at an average rate of 1.8 m/year (Al-Saleh, 1992). According to Al-Hassoun (1997), a fall in water levels has occurred in the wells at the centre of the Alwasia aquifer around Riyadh. This could reach 43.3 m for the period from 1981 to 2010, if the recent water pumping rates of 190000 m^3/day continue. Over the last decade, ever increasing volumes of water have been pumped from aquifers in Saudi Arabia, mainly for irrigation purposes (Al-Hassaun, 1997).

In Saudi Arabia, the majority of the abstracted water is used for irrigation, and wheat cultivation is one of the heaviest consumers. However, Saudi Arabia’s agriculture will face a greatly increased level of stress in the future because of the combined effects of global warming and population growth (Pauwa et al., 2000).

Ferrari et al. (1999) concluded that climate change could place particular stress on water resources in arid countries. Climate change may further decrease the stream flow and groundwater recharge in many water-stressed countries, for example in central Asia, southern Africa, and countries around the Mediterranean (IPCC, 2001c). Some GCM based scenarios for tropical and subtropical regions (including Saudi Arabia), indicate that the Middle East, as a water-stressed region, will experience a decrease in water supply (Alkolibi, 2002) because of the negative effects of climate change. Jones (1999) concurred with this, stating that in many regions of the world climate change over the coming decades may add measurable stress to water resources.

Arnell and King (1997) estimated changes in runoff and water resources globally under climate change using a macroscale hydrological model, with a spatial resolution of 0.5° x 0.5°, to simulate daily runoff given changes in rainfall, temperature and ET_O derived from GCMs. They found for the 2080s decreases in runoff in the Arabian Peninsula, and in the study area in particular, of between 0% and 50%. Jones (1999) commented that most of the projected increases in runoff may occur in regions that are not currently stressed, but that most of the decreases may occur in areas that are already stressed under the present climate.

IPCC (2001c) suggests that whereas climate change is unlikely to have a major effect on domestic and industrial water demands in general, it may considerably affect irrigation withdrawals; although this depends on how increases in evaporation are offset or exaggerated by changes in rainfall. However, Downing et al. (2003) wrote that since the mid-1990s, water companies in the UK have been concerned enough about the issue to undertake additional studies into climate change impacts on demand. Such a study by Downing et al. (2003) evaluated the relationships between climatic variability and both average and peak demand, although their concern was not with any particular sector. An earlier study by Herrington (1996) analysed the impacts of climate change on water demand in

England and Wales and concluded that a 1.1°C rise in temperature by 2021 would increase water demand for agriculture by 12%.

Although groundwater is a major source of fresh water across much of the world, particularly in the rural areas of arid and semi-arid regions, there has been very little research on the potential effects of climate change on it (IPCC, 2001c). Yusoff et al. (2002) investigated the impacts of climate change on the Chalk aquifer in west Norfolk using HadCM2 GCM and two emissions scenarios (medium-high (MH) and medium-low (ML)). They found that by the 2020s with ML, the annual recharge was 6% greater than the present value (1980-1995 average), while the worst outcome was produced with the 2050s ML scenario, in which the annual recharge was 10% less than the present value. IPCC (2001c) cited that Bouraoui et al. (1999) had concluded that substantial reductions in groundwater recharge near Grenoble, France, were almost entirely due to increases in evaporation during the recharge season.

2.5 Approaches to Calculating CWR in Irrigated Agriculture

This study presents a sensitivity analysis of irrigation water use to climate change through its effects on CWR. The FAO definition of CWR is:

> *''The depth of water needed to meet the water loss through ET_O of a disease-free crop, growing in a large field under non-restricted soil conditions including soil water and fertility, and achieving full production potential under a given growing environment.''* (Doorenbos and Pruitt, 1977, p.1).

The CWR of wheat depends on the loss of water through ET_O and is mainly a function of climatic factors, such as air temperature, solar radiation, relative humidity, wind speed, and agronomic factors like the stage of crop development

(Doorenbos et al., 1979). Calculating the water use for an irrigated crop, and its efficiency of use, are very important, especially in arid areas as CWR ratios vary substantially during the growing period, due to the changing crop canopy and climate conditions (Doorenbos and Pruitt, 1977). Therefore, knowledge of CWR is an important practical consideration in improving water use efficiency in irrigation (Tyagi et al., 2000). Estimates of CWR also have practical application in the scheduling of irrigation, the modelling of crop yield in relation to crop water use, and in irrigation project planning and management (Mohammad et al., 1994). In terms of efficiency, ICARDA (2001) reported that inefficient water use not only limits crop yields in the short term, but also undermines productivity in the longer term contributing to soil degradation and wider environmental damage.

Accurate calculations of CWR for the irrigation of wheat, especially in zones of high evaporation such as in the study area, are critical as there is a risk of increasing soil salinity (ICARDA, 2001). This is because high temperatures result in high evaporation rates, and irrigation that is consumed by evaporation leaves the remaining water more concentrated with salts (Kijne, 2003). Rosenzweig et al. (1995) also indicted that intensified evaporation increases the hazard of salt accumulation in the soil, and therefore, the efficient use of water is of particular concern to farmers and agricultural scientists. Knowledge of the optimum quantities of irrigation water for application is essential in order to obtain the maximum sustainable yields of different crops as economically as possible (Brown,1999), and to conserve water resources and soil quality. These are important objectives in areas such as Saudi Arabia, which experience water scarcity and soil salinization problems.

In Saudi Arabia and the study area, a number of researchers have estimated ET_O, CWR and irrigation efficiency. The first one was the in the Al-Ahsa region in 1977 and was conducted by the Leichtwesis Institute Research Team. They estimated the CWR for wheat at 414 mm (Al-Omran et al., 1992). The MAW (1988) estimated CWR in 13 climatological areas of the Kingdom, using a modified

Penman method as outlined by the FAO Irrigation and Drainage Paper No 24, and calculated that CWR (plus leaching requirement) for wheat in the Gassim area under centre pivots was between 5966 and 9732 m^3/ha/season for water quality in the range of 0.78 to 6.25 mmhos/cm, respectively. For surface irrigation methods, CWR values were found to range between 7593 and 13707 m^3/ha/season, for water quality ranging from 0.78 to 6.25 mmhos/cm, respectively. However, this study met with some criticism owing to the climatic data used; Al-Omran et al. (1992) pointed out some errors in the temperature data. Another early study was conducted by Mustafa et al. (1989), who also evaluated CWR for wheat in Saudi Arabia, and found CWR ranging from 3790 to 6740 m^3/ha/season.

In addition, Mustafa et al. (1989) calculated ET_O according to the Jensen-Haise method and estimated CWR for wheat in Saudi Arabia at from 379 to 674 mm. On the other hand, Algshuan (1990) estimated ET_O using the Thornthwaite method and she found that ET_O ranges from 46 to 231 mm/month in January and July, respectively. Basahi (2002) also estimated ET_O for Saudi Arabia, but using the Penman-Monteith equation modified by FAO, and found the average ET_O for the Gassim area to be 6.4 mm/day, which is about 534 mm/season for wheat. Similarly, Al-Omran et al. (1992) calculated ET_O, but according to the Jensen-Haise method, and estimated the CWR for wheat in the eastern and central regions of Saudi Arabia at 552 mm/season.

Al Al-Shaikh (1993) in her study to the south of Riyadh city, estimated actual water applied (AWA) for wheat under the surface method at between 3270 and 11437 m^3/ha/season, although under the centre pivot system it was between 2012 and 5417 m^3/ha/season. On the other hand, she calculated CWR for wheat at ranging from 1798 to 2125 m^3/ha/season. Moreover she estimated the field water use efficiency (FWUE) for the same crop under the surface method at between 0.10 and 0.46 k/m^3 (crop yield per cubic metres) and under the centre pivot at between 0.19 and 0.80 k/m^3. Kassem et al. (2003) also estimated crop water use efficiency

(CWUE) and field water use efficiency (FWUE) in the Gassim area for the barley crop, and they found that the highest values of CWUE and FWUE were 1.53 and 0.77 k/m^3 respectively. Al Al-Shaikh (1995), estimated CWR for wheat in Riyadh, and she found CWR ranging from 1050 to 1258 m^3/ha/season, when using the Al-Ahsa equation (Al-Taher, 1992a).

Al-Taher et al. (1992) calculated the CWR for wheat in Ad Dawadimi located to the south of the Gassim area, using the Blaney and Criddle method, and found CWR ranging from 3307 to 3829 m^3/ha/season, but importantly, they also calculated field irrigation efficiency (IE) (using formula 3.7, see Chapter 3) for wheat under centre pivots and they found the values for IE ranged from 27% to 78%. Another study, again by Al-Taher (1994), in the Yabrin oasis in the southern Saudi Arabia found that the values for IE for alfalfa crops ranged from 19% to 70%, whereas he found CWR for date palms at 26440 m^3/ha/year, using the Jensn-Haise method. Abderrahman et al. (1993) calculated CWR for date palms in five selected date palm regions in Saudi Arabia, one of them in the Gassim area, using a modified Penman method. They found CWR for date palms in the Gassim area to be 37911 m^3/ha/year under the surface irrigation method, whereas under the drip irrigation method at 23165 m^3/ha/year. Additionally, Al-Taher (1992b) had also estimated CWR for date palms in the Al-Ahsa region and found it to be 33830 m^3/ha/year. These values are annual rather than seasonal as date palms are considered as a permanent plant.

Climate and the date of crop planting are key factors in influencing CWR. Al-Taher (1998) asserted that in eastern Saudi Arabia the climate is one of the most important environmental factors with a direct effect on CWR. Al-Taher (1993) had already calculated the CWR for wheat using the Jensen-Haise equation, and he found that it ranged from 4448 to 6683 m^3/ha/season according to the planting date, and thus concluded that the planting date is a critical factor affecting the CWR for wheat. He estimated that 70% of the variations in CWR values in the Gassim area are due to the influence of different planting dates. Table 2.3

summaries the finding of research into CWR in Saudi Arabia. The differences between the results of CWR could be because of differences in methods, locations, Kc (adjustment factor for crop stage of growth), planting dates, LWGS and weather stations.

Study Authors	**Location**	**Crop**	**CWR m^3/ha/season**	**How calculated**
Al-Taher (1993)	Gassim	Wheat	4448 to 6683	Jensen-Haise (Jensen, 1973)
MAW, (1988)	Gassim	Wheat	5966 - 9732[1] 7593 - 13707[2]	Penman +LR
Al-Omran et al. (1992)	central regions	Wheat	5520	Jensen-Haise
Al Al-Shaikh (1993)	Alkarj	Wheat	1798 to 2125	Jensen-Haise
Al Al-Shaikh (1995)	Riyadh	Wheat	1050 to 1258	Al-Ahsa equation (Al-Taher, 1992a)
Mustafa et al. (1989)	Saudi Arabia	Wheat	3790 - 6740	Jensen-Haise
Leichtwesis, (1977)	Al-Ahsa	Wheat	4140	n/a
Al-Taher et al. (1992)	Ad Dawadimi	Wheat	3307 to 3829	Blaney and Criddle
Mustafa et al. (1989)	Saudi Arabia	Wheat	3790 to 6740	n/a
Al-Taher (1994)	Yabrin oasis	Date palms	26440	Jensen-Haise
Al-Taher (1992a)	Al-Ahsa	Date palms	33830	Jensen-Haise
Abderrahman et al. (1993)	Gassim	Date palms	37911 (surface) 23165 (drip)	modified Penman

Table 2.3: A summary of studies in Saudi Arabia to estimate CWR.

[1] For centre pivots irrigation methods.
[2] For surface irrigation methods.

2.6 Growing Wheat in Saudi Arabia

Wheat has been selected for this study because it is currently the most important irrigated crop in Saudi Arabia, has a widespread coverage, is the principal staple food for the majority of the population, and has important economic value. According to FAO (1997), in 1988 wheat consumed almost 40% of the total quantity of irrigation water and covered almost 62% of the total irrigated area in Saudi Arabia. The main production area for wheat in Saudi Arabia is the central part of the country, particularly around Gassim. There is normally one crop of winter wheat per season. The crop is always sown in late autumn and matures in early summer; the wheat-growing season corresponds to the wettest period of the year. Nimah et al. (1986) reported that the wheat-planting period in the study area extends from the 15th of November to the 1st of January. In addition, Eissa (1994) agreed with several bulletins published by the MAW that the period for wheat planting in Saudi Arabia should lie between mid-November and mid-December. Planting wheat outside of December is possible, but planting before or after this period may result in yield reductions because it would be out of the optimum temperatures range. Most of the agricultural companies in Saudi Arabia plant their crops over an extended period of time for two reasons: the extent of the areas cultivated by each company, and the limited number of planting machines available to sow the wheat crop. For example, Al-Gassim Company planted their wheat crop over a range of 78 days; from the 10th of December to the 25th of February in the 1985/86 season (Al-Qassim Agricultural Company, 1986).

The production of wheat is affected by soil, water, climate and crop management factors (Hussain and Al-Jaloud, 1998). Nevertheless, climate is critical, and raises the question; how is wheat production likely to be affected by climate change? In fact, winter wheat in arid areas, including Saudi Arabia, is particularly vulnerable to variations in winter temperature because as already noted, in such areas it grows

close to its maximum temperature tolerance limits (Alkolibi, 2002). This question is explored in Chapter 7.

2.7 Discussion and Conclusions

The majority of the studies in this review have concentrated on climate change and its possible effects in agriculture, especially on crop yields, but only a few studies have looked at the impacts of these changes on CWR and water resources. Brumbelow et al. (2001) regretted that few studies have assessed changing irrigation requirements under climate change. In Saudi Arabia to date there has been no single study that discusses future climate change in the 21st century and focuses on the outputs of GCMs for a particular sector.

The main themes derived from this review are as follows;

- There have been very few studies of climate variability in Saudi Arabia, and the few in existence show that it is an arid region, receiving only 80 to 140 mm of rainfall per year.
- Very few studies have been conducted into climate change in Saudi Arabia, and those that have been published do not discuss climate change based on the output of GCMs in any detail or its impact on agriculture and water resources. Climate change will probably have a variety of consequences for agriculture; some positive and some negative. Other factors being equal, warmer temperatures will increase ET_O, which will pose a multifaceted threat to Saudi Arabia in general and to its agriculture and water supplies in particular. Higher ET_O rates, will alter soil moisture and infiltration rates, accelerate transpiration from plants, cause moisture stress, and increase the hazard of salt accumulation in the soil.
- In middle latitudes, such as the study area, higher temperatures may decrease the length of the growing season. Higher frequency and absolute temperatures of extreme events may have negative consequences on crop

yield, especially as wheat in Gassim is currently grown close to its thermal tolerance limits.

- In Saudi Arabia, and in the study area, a number of researchers have estimated ET_O, CWR and irrigation efficiency using several methods; the results highlight differences due to crop type, ET_O estimation method and location.
- The effects of climate change on irrigation water demand depend on the differing GCM scenarios and methods used for estimating ET_O, and on the geographical location. The situation is further complicated by the uncertain effects of direct CO_2 increase on crop water use efficiency.
- The government owns the water resources in Saudi Arabia, and the MAW which is the body responsible for the implementation of policy. The majority of the abstracted water is used for irrigation, and wheat cultivation is one of the heaviest consumers. At present, depletion of this non-renewable fossil water is taking place at an alarming rate.
- Climate change could place additional stress on water resources. Saudi Arabia's agriculture will face even more stress in the future because of population growth. Therefore, knowledge of CWR under both the current climate and under climate change is an important practical consideration.
- There have been no integrated studies of climate change, agriculture and water use in the region. Higher temperatures and possibly higher ET_O are likely to increase demand for irrigation water in this region, where water is relatively scarce and groundwater levels are falling. Consequently, this study aims to contribute to water management in one of the main agricultural areas in Saudi Arabia: Gassim. In 1992 Gassim produced 1270506 tonnes of cereal, which represented 27% of the total crop production of Saudi Arabia. However, Gassim represents just 3.5% of the total land area of Saudi Arabia.

- Wheat has been selected for study because it is largest crop under irrigation in Saudi Arabia and is the most important staple food for the majority of its population.
- To achieve the above this study will investigate the current climate variability/trend, climate change, and their impacts on ET_O and CWR in Gassim. Some focus is given to the sensitivity of ET_O and CWR to climate change with respect to wheat in the study area. The study is undertaken using field results from a case study of two types of farms (commercial and traditional) in the Gassim area to examine their actual water use in relation to estimated CWR. This is used in order to assess the relative importance of climate change compared to other factors such as water management.

Chapter Three: Data and Methods

3.1 Introduction

Chapter 2 has presented a review of previous studies on the climate of Saudi Arabia, ET_o, CWR, and future climate change and its potential impacts on agriculture and water resources. This chapter now introduces the data and the methods used in the research. The first section (3.2) defines the framework for the sampling design of the fieldwork on farms in Gassim. The second section (3.3) introduces the data sets that were collected from the study area, and the GCM data used to construct climate scenarios. This is followed by a short overview of the statistical analysis methods used in the study. Section 3.4 introduces the methods used in the fieldwork, followed by an explanation of the FAO approach to calculating CWR, and a discussion of the methods available for estimating irrigation efficiency (IE), leaching requirements (LR) and irrigation scheduling (IS) (these are defined in Sections 5.12, 5.9 and 5.13, respectively). The final section introduces the methods used to determine the potential impact of climate change on ET_O, CWR, and the LWGS in Gassim.

3.2 Sampling Design: Choice of Farms for Collection of Field Data

Field studies were carried out in the Gassim area during winter 2003, in order to select sample farms and collect data on irrigation water use. Two CFs and six TFs were selected for study. The limited amount of time available for field work restricted sample sizes. However, agricultural practices and environmental conditions are fairly homogeneous in the region so that the results obtained here should be representative of the situation across Gassim. The TFs were chosen principally on the basis of random sampling from among the limited number of

farms that grow wheat in the study area. One CF was chosen as it is the largest in the study area, in order to represent commercial large-scale farming modes. The second was randomly chosen from among the other smaller CFs. Field observations were made with farmers to measure the AWA during irrigation applications and to obtain samples of water and soil from each farm (for more details see Section 5.2). The observation period covered four sowing dates (mid-November, beginning of December, mid-December, and mid-January), for the average growing season length of 130 days. Details of measurement procedure and frequency are presented in Chapter 5.

3.3 Climate Data: Observed and GCM

Sometimes, it can be difficult to obtain data or information from government offices in Saudi Arabia due to inconsistent procedures and lack of accountability, and this problem is faced by many researchers. Even the climatic data required for this study were difficult to collect, and a great deal of time was required to obtain hard copies or information via e-mail from the MAW. Nevertheless, daily rainfall data for eleven rain gauges in the study area were eventually provided on hard copy for the period 1971-2000, and were entered into the computer by hand.

A small amount of groundwater level data was also used for the study. Obtaining these data from the MAW was also very difficult as access by the public to this information is not easy, and the records are generally used for internal Ministry purposes. However, for this project, short series were provided for five wells in the Gassim area from 1997 to 2001 as hard copy. Information on soil characteristics on the case study farms was needed for estimating CWR and IS. Soil samples were collected from each farm in the study area by digging soil pits and sampling at four levels (0-25, 25-50, 50-75, 75-100 cm) (see Section 5.5).

3.3.1 Details of the Weather Station in Gassim

Unizah weather station records provided the majority of the climate data used for this study, at latitude 26° 04´ N, longitude 43° 56´ E, with a site elevation of 724m. The MAW (Hydrology Section) provided monthly time series of maximum and minimum temperature (and daily), sunshine, wind speed, relative humidity, cloud cover and total rainfall (and daily) for the station, for a 30-year period (1971-2000). The exceptions were sunshine duration, only available for 1976-2000, and cloud cover, only available for 1985-1998 (see Tables 3.1 and 3.2). All these series were prepared for analysis by careful quality control, by checking visually for errors and break points in the series. A similar quality control procedure was performed for the eleven daily rainfall series provided by the MAW (as discussed above).

All these data were utilized for investigating the observed climate (Chapter 4) and for calculating ET_O and CWR (Chapter 5). They were also used in chapter 6 to define a baseline climate to which to apply climate change scenarios.

Parameters	**Period**	**Available**	**Period**
Max temperature (°C)	1971-2000	Y	Daily
Min temperature (°C)	1971-2000	Y	Daily
Rainfall (mm)	1971-2000	Y	Daily
Relative humidity (%)	1971-2000	Y	Monthly
Wind speed (m/s)	1971-2000	Y	Monthly
Sunshine (hour)	1976-2000	Y	Monthly
Evaporation (mm)	1971-2000	Y	Monthly
Cloud cover (tenths)	1985-1998	Y	Monthly

Table 3.1: The meteorological data of Unizah weather station used in this study.

No	Station name	Latitude °N	Longitude °E	Altitude(m)	Available data (years)	Missing data (%)
1	**Usaym**	26.35	42.28	940	23	23.3
2	**Unizah**	26.04	43.56	724	18	40
3	**Uqlat As Auqur**	25.50	42.11	740	24	20
4	**Samirah**	26.29	42.07	950	28	6.7
5	**Nuqra**	25.35	41.26	930	26	13.3
6	**Nabhaniyah**	25.51	43.04	760	22	26.7
7	**Fawwarah**	26.03	42.38	810	30	0.0
8	**Dukhnah**	25.21	43.37	800	29	3.3
9	**Dhala Rasheed**	25.28	42.53	790	23	23.3
10	**Buraydah**	26.20	43.58	630	27	10.0
11	**Arjah**	25.16	40.49	1040	19	36.7

Table 3.2: Rain gauges daily data used in the study.

3.3.2 General Circulation Model (GCM) Output

For the purpose of investigating and understanding climate change in the Gassim area, two GHG emissions scenarios that cover a range of the possible future emission scenarios generated by the IPCC Special Report on Emissions Scenarios (SRES), were used. The scenarios are referred to as A2 (high emissions) and B2 (medium emissions) (more details are presented in Section 6.3.1). The climate change scenarios were produced for two study time horizons, defined as the 2020s (2015-2039) and 2080s (2075-2099).

Three different GCMs were used to develop climate change scenarios for assessing the impact of climate change. The reason for the choice of three models instead of one is that different GCMs may simulate the observed climate better than others in particular regions and, importantly for impacts studies, they may produce different climate changes (especially with rainfall).

The GCM output was obtained from the IPCC Data Distribution Centre (DDC,

2004) (http://ipcc-ddc.cru.uea.ac.uk/dkrz/dkrz_index.html). The outputs of GCMs have been widely used to explore impacts on, for example, agriculture or irrigation systems, and how they might respond to an evolving climate. Table 3.3 shows the characteristics of the three GCMs used here with the SRES emissions scenarios. These models were chosen because they are all state-of-the-art, SRES, coupled Atmosphere-Ocean (here after referred to as GCMs), and are transient simulations. These GCM results have been widely used for impact assessments. Table 3.4 shows the variables available for the three GCMs as monthly average values and Table 3.5 shows the grid box coordinates that represent the study area in each model (see also Figure 6.8).

The three models are:

1. CGCM2 (Canadian Climate Centre) (Flato and Boer, 2001).
2. The UK HadCM3 (Hadley Centre for Climate Prediction and Research) (Mitchell et al., 1998; Gregory and Lowe, 2000; Johns et al., 2001). Arnell, (2004) stated that HadCM3 is the most recent version of the Hadley Centre GCM to be used for projecting the climatic effects of future emissions scenarios.
3. ECHAM4/OPYC3 (the Max-Planck-Institute for Meteorology (MPI) and Deutsches Klimarechenzentrum (DKRZ) in Hamburg, Germany) (Stendel et al., 2000).

Further details can be found on the IPCC DDC website (address given above).

> *"A popular climatological baseline period is a 30-year "normal" period as defined by the World Meteorological Organization (WMO)"* (IPCC-TGCIA, 1999, p. 7).

The current WMO climatological baseline period is 1961-1990. However, in this study the baseline is 1971-2000 as some data were missing from the records at Unizah station in the period before 1971, and because this new 30-year standard has become widely recognized worldwide (IPCC-TGCIA, 1999). Further details of the use and analysis of these data area presented in Chapter 6.

Model name	HadCM3	CGCM2	ECHAM4/OPYC
Centre	UKMO	CCCma	DKRZ
Country of origin	UK	Canada	Germany
Resolution lat. * long.	2.5 * 3.75°	3.8 * 3.8°	2.8 * 2.8°
Ocean resolution	1.25 x 1.25°	1.8 x 1.8°	2.8 x 2.8°
Scenarios A2	Y	Y	Y
Scenarios B2	Y	Y	Y

Table 3.3: Characteristics of the three GCMs used in this study. Adapted from the IPCC's Data Distribution Centre and from Hulme et al. (2001).

Y = Data available.

Model name	Temperature	Rainfall	Humidity	Wind speed	Solar radiation	Cloud cover
HadCM3	Y	Y	Y	Y	Y	Y
CGCM2	Y	Y	Y	Y	Y	-
ECHAM4/OPYC	Y	Y	Y	Y	Y	-

Table 3.4: Variables available from the three GCMs as monthly average values. Y = Data available.

Model name	Grid Box	Latitude	Longitude
HadCM3	1	25.00° N	41.25° E
CGCM2	1	27.83° N	45.00° E
ECHAM4/OPYC	1	26.51° N	42.19° E

Table 3.5: Grid box centre coordinates representing the study area in each model.

3.4 Statistical Methods for Analysis of Climate Data

In terms of data processing, a number of methods were used in this study in order to investigate recent climate variability in the area, and future climate scenarios. Climatological data analysis can be carried out through graphical or analytical

procedures: graphical methods used here generally consist of time series plots; analytical methods used are listed in Table 3.6. These techniques are standard and widely used in climatology, descriptions can be found in general texts on climate analysis and are not repeated here.

Statistical method	Used
Standard deviation	Chapter 4
Coefficient of variation	Chapter 4
Pearson correlation coefficient	Chapter 4
Spearman's Rank Correlation	Chapter 5
Trend analysis (Linear regression)	Chapters 4,6 and 7
Percentile analysis	Chapter 6
T-test	Chapter 6

Table 3.6: The statistical approaches used in this study.

3.5 Methods in Field: Estimating the Actual Water Applied during Irrigation Applications on Each Farm

One of the aims of this study is to estimate AWA through irrigation, for the TFs and the CFs. Measurements of AWA took place during the fieldwork study in 2003. Firstly, measurements on the TFs were carried out as follows:

1. Identify a typical field/basin which can represent the farm's situation in terms of crop, size and soil type.
2. Measure the field/basin area length and width by tape.
3. V-Shape weirs obtained from Gassim University were installed in stream to estimate discharge (flow rate) (Picture 5.1).
4. Measure the head of water (H) that passes the V-Shape in centimeters; the measurement was taken three or four times in each farm.
5. Time the length of time needed to fill the field.
6. Use the weir (V-notch) equation 3.1 below to calculate the AWA discharge.

7. The measurements were made between three and four times per farm, and then the average was calculated for each to represent an average application volume.

$$Q = \frac{8}{15}\sqrt{2g}.C_D \tan\frac{\theta}{2}.h\frac{5}{2} \tag{3.1}$$

(Withers et al., 1974)

Where Q discharge rate (m^3/sec),

C_D discharge coefficient =0.65,

h head of water (mm),

θ notch angle in degrees.

8. Finally, for the sprinkler irrigation method in the CFs, flow meters were used to measure the volume of AWA during irrigation periods on the farms. The duration and frequency of applications were taken from the farm's records.

3.6 The FAO Approach for Calculating CWR

3.6.1 Estimating Reference Evapotranspiration

Where estimating a reference ET_O , Allen et al. (1998, p.17) note that:

> *"A large number of more or less empirical methods have been developed over the last 50 years by numerous scientists and specialists worldwide to estimate ET_O from different climatic variables".*

In this study a combination method was employed, based on the FAO Penman-Monteith equation (see Allen et al., 1998). Combination methods require more data than temperature and radiation methods, and require average monthly air temperatures in degrees Celsius (°C), relative humidity (%), sunshine duration

(hour) and wind speed (m/s) measured at 2 m above ground level. Jacobs (2001, p.9) indicated that:

> *"the combination type of equations give the best results for a variety of vegetated surfaces and climates; and their application is suitable for those locations where measured data on temperature, wind and sunshine duration or radiation are available".*

In the current study, monthly ET_O values were estimated using a FORTRAN software program, written by the researcher to perform the ET_O calculations. The program results were validated by comparison with hand calculations and results of the FAO CROPWAT program (Version 4.2. 1998, website - http://www.fao.org/landandwater/aglw/cropwat.stm). This estimation was done according to the following equation:

$$ET_o = \frac{0.408\,\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)} \quad (3.2)$$

(Allen et al., 1998)

Where ET_O reference evapotranspiration [mm day^{-1}],

R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],

G soil heat flux density [MJ m^{-2} day^{-1}],

T average daily air temperature at 2 m height [°C],

u_2 wind speed at 2 m height [m s^{-1}],

e_s saturation vapour pressure [kPa],

e_a actual vapour pressure [kPa],

e_s-e_a saturation vapour pressure deficit [kPa],

Δ slope vapour pressure curve [kPa °C^{-1}],

γ psychrometric constant [kPa °C^{-1}].

3.6.2 Estimating CWR

CWR can be obtained from an estimation of ET_O and a crop coefficient (K_c). Kassam et al. (2001, p.2) reported that:

> *"Owing to the difficulty of obtaining readily available and accurate field measurements, the estimation of CWR as derived from estimating crop ET_O according to standardized crop and climatic conditions […] The water requirements of a given crop were derived through a crop coefficient that integrated the combined effects of crop transpiration and soil evaporation into a single crop coefficient, according to the following relationship".*

$$CWR = Kc \, . \, ET_o \tag{3.3}$$

(Allen et al., 1998)

Where CWR the crop evapotranspiration, computed for optimal conditions,
ET_O reference crop evapotranspiration,
Kc crop coefficient.

The value of Kc for a specific crop is usually obtained from the literature based on its growth season and planted area (Yu et al., 2002). Local values of Kc for wheat were used for this study estimated by the MAW (1988) in four development stages as shown in Figure 3.1. In general, the Kc curve follows values close to those presented by Doorenbos and Pruitt (1977). The Kc curve shows the initial stage with low values, and then a rising limb during the period of increased growth, and a peak where the crop attains maximum cover and growth, followed by a decreasing limb when leaves start to shed at the end of the growth cycle

(Abdelhadi et al., 2000). The MAW (1988) described the fourth growth stage as:

Stage 1. (Initial stage) Germination and early growth (Ground cover less than 10%), therefore the Kc value is a small fraction (0.55).
Stage 2. (Crop development stage). From the end of the initial stage to the attainment of effective full ground cover (ground cover 70-80%).
Stage 3. (Mid-season Stage). From the end of the crop development stage to the time of the start of maturation, where the Kc value reaches its highest value.
Stage 4. (Late season stage) From the end of the mid-season stage until full maturity or harvest; the Kc value in this stage decreases gradually, down to 50% or less.

CWR values were calculated in millimeters, and converted into m^3 per hectare, using the following equation;

$$\text{Amount in mm x 10} = \text{m}^3 \text{ per hectare.} \tag{3.4}$$

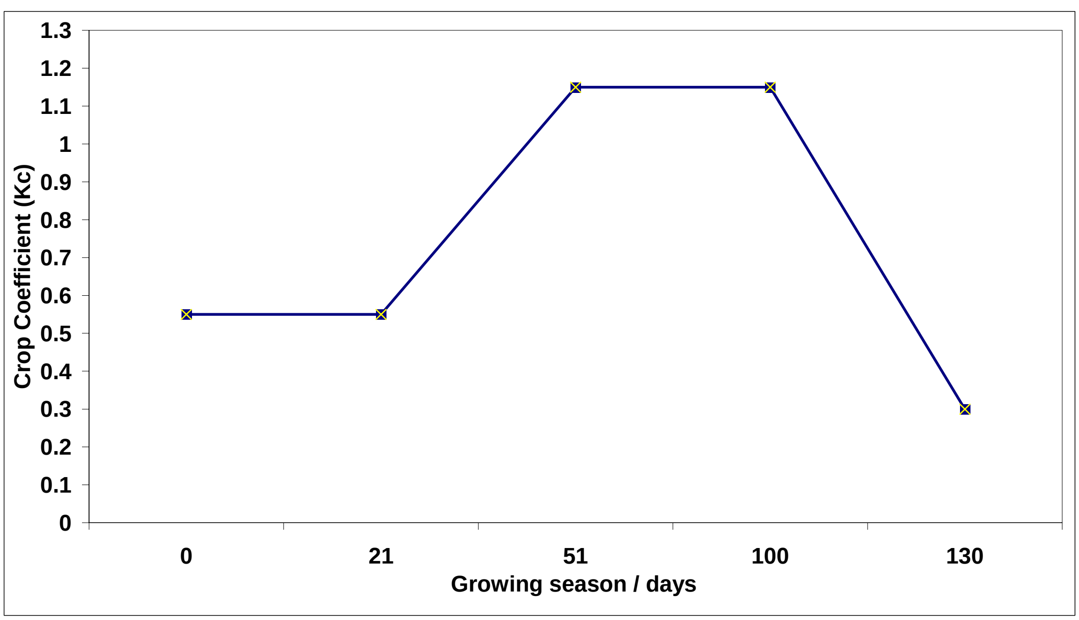


Figure 3.1: Length of growing season and crop development stages for wheat in the study area (MAW, 1988).

3.6.3 Determining the Field and Crop Water Use Efficiency (FWUE and CWUE)

The volume of water used in the field to produce a crop mass is often described in kg/m^3. FWUE is defined as the ratio of grain yield to the total amount of water used in the field (I.A.R.I, 1977). The FWUE was determined for the two types of farms according to the following equation:

$$FWUE = \frac{Y}{AWA} \tag{3.5}$$

(Begg & Turner, 1976)

Where $FWUE$ field water use efficiency (%),

Y the seed yield (kg/ha),

AWA applied water (m^3/ha).

CWUE is the ratio of crop yield Y to the amount of water depleted by the crop in the process of ET_O (I.A.R.I, 1977), and described as:

$$CWUE = \frac{Y}{ET_O} \tag{3.6}$$

(Begg & Turner, 1976)

Where $CWUE$ crop water use efficiency (%),

Y the seed yield (kg/ha),

ET_O evapotranspiration.

3.6.4 Determining the Irrigation Efficiency (IE)

IE has traditionally been calculated according to the following formula developed by Jensen et al. (1967):

$$IE = \frac{CWR + LR - R}{AWA} \times 100 \qquad (3.7)$$

Where IE irrigation efficiency,
CWR crop water requirements,
LR leaching requirements,
R rainfall,
AWA actual water applied.

As the rainfall in the study area is very low (see Sections 4.2.5 and 5.8), the preceding formula can be rewritten as developed by Al-Taher (1987),

$$IE = \frac{CWR + LR}{AWA} \times 100 \qquad (3.8)$$

3.7 Other Factors Relevant for Calculating CWR

3.7.1 Determining the Leaching Requirement (LR)

The LR, for soils with good drainage and where rainfall is very low, may be obtained as follows:

$$LR = \frac{EC_w}{2MaxEC_e} \times \frac{1}{LE} \qquad (3.9)$$

(Ayers and Westcott, 1976) & (MAW, 1988)

Where LR leaching requirement, expressed as a ratio or per cent,
EC_w electrical conductivity of the irrigation water (mmhos/cm),
EC_e electrical conductivity of the soil saturation extract for a given crop (mmhos/cm),

$2MaxEC_e$ maximum tolerable electrical conductivity of the soil saturation extract for a given crop (for wheat 20 mmhos/cm),

LE leaching efficiency, assumed to be 90% for sandy and sandy loam soils.

3.7.2 Estimating the Gross Irrigation Requirements (GIR)

Estimating the gross irrigation requirement (GIR) (GIR is defined in Sections 5.10), may be done according to the following equation:

$$GIR = \frac{CWR}{eff} \times \frac{1}{1 - LR} (m^3 / ha) \qquad (3.10)$$

(MAW, 1988)

Where GIR gross irrigation requirement (m^3/ha),

CWR crop water requirement (m^3/ha),

LR leaching requirement,

eff efficiency of the irrigation method. It is generally estimated from widely available figures for different types of irrigation methods (see discussion in Section 5.10).

3.7.3 Determining the Irrigation Schedule (IS)

Determining the IS can be obtained by using the FAO CROPWAT model for irrigation planning and management. This was developed by the FAO Land and Water Development Division (FAO, 1992). Climate, soil and crop data from the field study in the Gassim area were used to evaluate the utility of the CROPWAT model in simulating the IS. The IS is a theoretical and optimized figure produced by CROPWAT. Of course practice in the field may be quite different. This issue is discussed in Chapter 5.

3.7.3.1 CROPWAT Input Data

Estimating the IS utilizes inputs of climatic, crop and soil data, all of which are listed in Tables 3.7 – 3.9.

Parameter	**Temperature**	**Humidity**	**Wind speed**	**Sunshine**
Climate	Y	Y	Y	Y
	Average monthly from 1976-2000			

Table 3.7: The climate parameters used for the estimation of IS.

Stages of crop growth	**Initial**	**Dev.**	**Mid.**	**Late.**
Crop Coefficients Kc	0.55	0.65	1.15	0.3
Stage Lengths (Days)	20	30	50	30
Rooting Depths (m)	0.30	-	1.20	1.20
Depletion Levels (P)	0.50	-	0.50	0.80
Yield Response Factor (Ky)	0.40	-	0.60	0.40
Percentage of total area planted to crop				(100%)
First planting	15/11	01/12	15/12	15/01
First harvesting	25/03	10/04	24/04	25/05

Table 3.8: The crop parameters used for the estimation of IS.

Parameter
Total available soil moisture (mm/m depth)*
Initial soil moisture depletion (% of total available moisture) (50%)
Initial available soil moisture (mm/m depth)

Table 3.9: The soil parameters used for the estimation of IS.
*This was adjusted it to meet actual conditions.

3.8 Estimating CWR under Climate Change Conditions

Chapter 5 presents estimates of ET_O and CWR for the current climate and these analyses are then repeated for future climate projections in Chapter 7. In addition, estimates are also made of how the LWGS will change under the projected climate changes.

3.8.1 Determining the Potential Impact of Climate Change on ET_O, CWR and LWGS

ET_O and CWR are estimated for the current baseline (1976-2000) climate, utilizing a monthly data series based on the FAO's Penman-Monteith equation for ET_O (see Section 3.6.1) and for CWR (see Section 3.6.2). The future climate change scenarios are then calculated using results from three GCMs. These future climates are used to estimate changes in ET_O and CWR relative to the baseline. The LWGS was estimated according to the number of days where the temperature was ≤30°C, over the 30 year period (1971-2000). This was performed by using the actual daily maximum temperatures, and then by using daily maximum temperatures from HadCM3 (daily data were only available for HadCM3).

3.8.2 Calculation of Relative Humidity from GCM Output

HadCM3 is the only GCM of the three used in this study that provides relative humidity as an output variable. The CGCM2 model provides specific humidity, and ECHAM4 provides dew point. Therefore, specific humidity and dew point were converted to relative humidity in order to make comparisons between the three models possible.

Relative humidity can be calculated from the formula:

$$RH = (e \;/\; e_s) * 100\% \qquad (3.11)$$

Where e actual vapour pressure in mb,

e_s saturation vapour pressure in mb.

Where e_s is a function of Temperature while e is function of Dew point Temperature (Td). e_s can be calculated using the Clausius-Calpeyron equation (Rogers et al., 1989):

$$e_s(T) = e_s(T_o)\exp[\frac{L}{R_v}(\frac{1}{T_o} - \frac{1}{T})] \quad (3.12)$$

Where T_o 273.15 K (freezing temperature for water),

$e_s(T_o)$ 6.11 mb (vapour pressure at freezing),

L 2.5x10^6 J kg^{-1} (latent heat of vaporization),

R_v 461.4 J kg^{-1} deg^{-1} (individual gas constant for water vapor).

Similarly, actual vapour pressure can be computed using the above equation but for dew point temperature:

$$e\ (Td) = e_s(T_o)\exp[\frac{L}{R_v}(\frac{1}{T_o} - \frac{1}{Td})] \quad (3.13)$$

CGCM2 provides specific humidity (q) instead of dew point temperature and therefore actual vapour pressure can be computed using the following formula:

e (actual vapour pressure)= q*p/ $\in$ (3.14)

Where $\in$ 0.622,

P pressure in mb.

The computation of e_s is similar to equation (3.12).

3.9 Conclusion

This chapter has presented the main analytical methods used in this study, and the main data sources. The methods and data sets can be summarised as follows:

Statistical methods for the analysis of climate data include: standard deviation, coefficient of variation, Pearson correlation coefficient, trend analysis (linear regression), percentile analysis, T-test, and regression. Field measurement methods were used for estimating AWA in the field, and a set of approaches based on FAO procedures used for estimating water use in irrigation: ET_O, CWR, FWUE, CWUE, IE, LR, GIR, LWGS and IS.

The data sources were mainly obtained from: the IPCC DDC (climate change data derived from three GCMs), the MAW (observed climate and groundwater data), and fieldwork. Where these data sources and methods are used in the following chapters, their limitations and uncertainties are also discussed in relation to interpretation of the results. The following chapter presents an analysis of the observed climate and the groundwater data obtained from the MAW.

Chapter Four: Climate Variability and Trends in Groundwater in Gassim

4.1 Introduction and Aims

This chapter introduces the climate regime in Saudi Arabia and Gassim. The first section presents an overview of the climatological features of Saudi Arabia and identifies their most important influences. This is followed by a detailed analysis of daily, seasonal and interannual variability of climate in Gassim in terms of temperature and rainfall, and four other important climate factors. The subsequent sections deal with water use in Saudi Arabia and Gassim, and groundwater distribution in Gassim. Groundwater abstractions, trends in groundwater levels, and groundwater quality are presented and the role of dams and reservoirs in the region is briefly discussed. The final section discusses the main results and presents key conclusions.

The first objective of this chapter is to examine the climatic situation in the study area, in order to analyse the spatial and temporal characteristics of rainfall and temperature in particular. The second objective is to explore one of the most important issues in environmental management in Saudi Arabia: water use and water resources management, in order to highlight the critical situation with regard to water availability and to provide a context for the analysis of water use in irrigation in Chapter 5. This issue is especially important in Gassim, and this is demonstrated through an investigation of groundwater withdrawals and trends in groundwater levels.

4.2 Observed Climate

4.2.1 Introduction to the Climate in Saudi Arabia

The Kingdom of Saudi Arabia, with an area of about 2.25 million km^2, occupies about 80% of the Arabian Peninsula. Saudi Arabia is located in Southwest Asia, between latitudes 16° 30’ and 30° 20’ N and longitudes 34° 40’ and 56° 00’ E. Saudi Arabia is located within the global desert zone, and forms part of a virtually unbroken belt of desert environment that extends for some 9300 km from the Atlantic coast of northwestern Africa to the Thar desert in northwestern India (Al-Sayari et al., 1978). Saudi Arabia is located in the subtropics, and is mainly arid according to Köppen’s classification (Battan, 1984 Figure 4.1). However, the southwestern region is characterized by high mountains and higher rainfall, due to its unique geographic and topographic features (MAW, 1984) and is classified as semi-arid.

The annual temperature range in Saudi Arabia is large (~20°C) (Almazroui, 1998). Generally, the climate in the summer (June to August) is extremely hot and dry and the maximum temperature in the shade frequently exceeds 48°C in most parts of the country. The temperature can at times exceed 50°C, especially in the southern deserts, where the lack of clouds results in considerable solar radiation (MAW, 1984). On the other hand, in winter (December to February), the climate is cool and dry, and sometimes winter temperatures drop below freezing in the central and northernmost parts of the country. In general, from May to October temperatures are very high causing excessive evaporation, whereas from November to April, the temperatures are moderate with cool nights and sunny days. Figure 4.2 shows a map of the average annual temperatures.

Rainfall in most of Saudi Arabia falls primarily as winter storms moving eastward from the Mediterranean Sea, and although it generally occurs between October and May, it is limited, irregular, and unreliable. Total rainfall has been estimated at

approximately 100 mm/year or less (Beaumont, 1981; Pike, 1983). The Asir mountain range in the southwest of the country is the only exception, where rainfall occurs in all seasons and the annual rainfall is greater than 500 mm/year but its variability between years is high (MAW, 1984; Figure 4.3).

In terms of moisture, Saudi Arabia is bordered by the seas of the Arabian Gulf in the east (the Persian Gulf) and by the Red Sea in the west. These create high relative humidity, at times exceeding 90% in the costal areas, however, they have little effect on the relative humidity inland, where, the humidity decreases to less than 10%, especially in summer months (MAW, 1984).

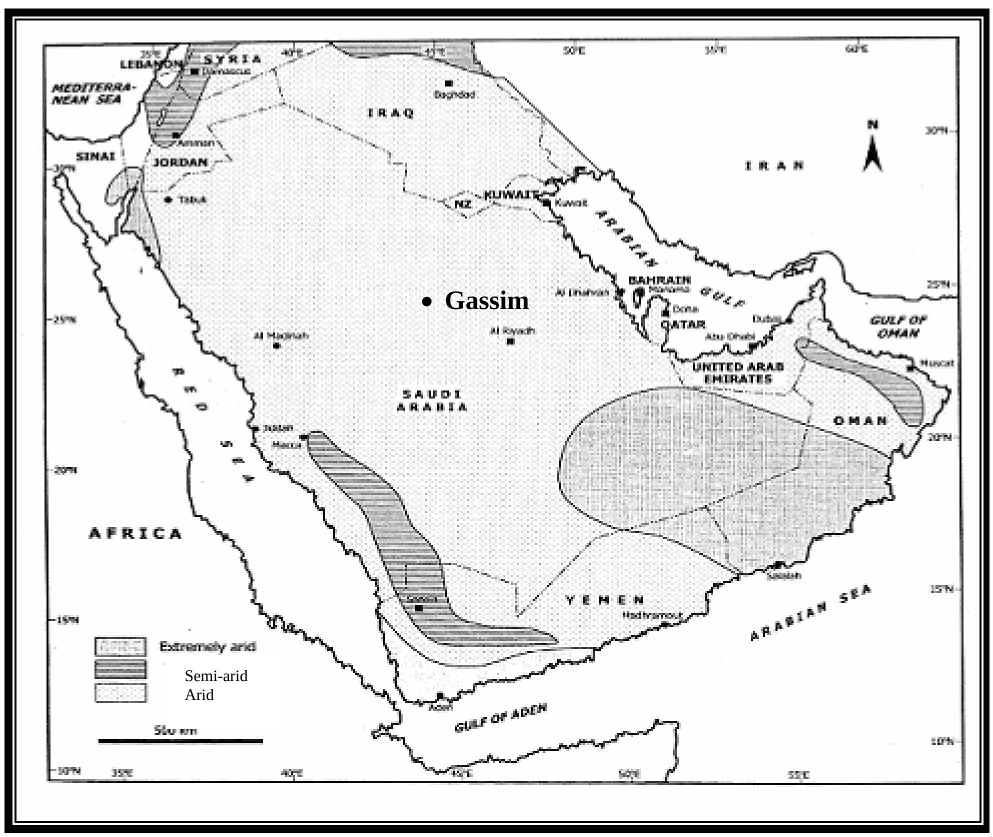


Figure 4.1: The main climatic zones in the Arabian Peninsula (modified from Alsharhan et al., 2001).

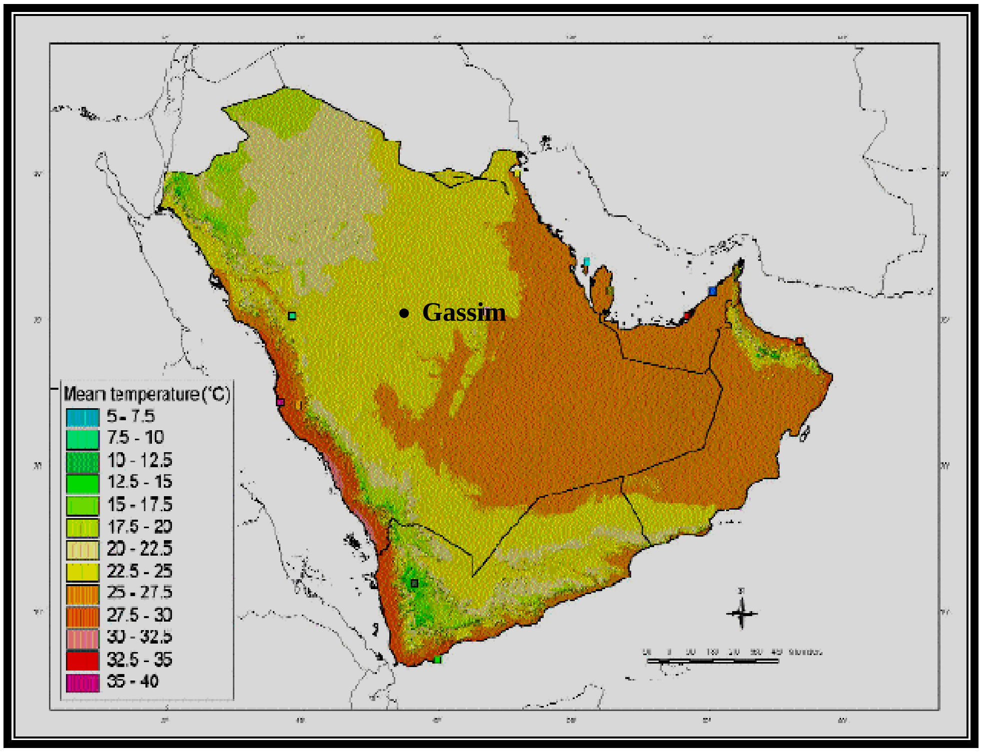


Figure 4.2: Average annual temperature of Arabian Peninsula (Source: De Pauw, 2002).

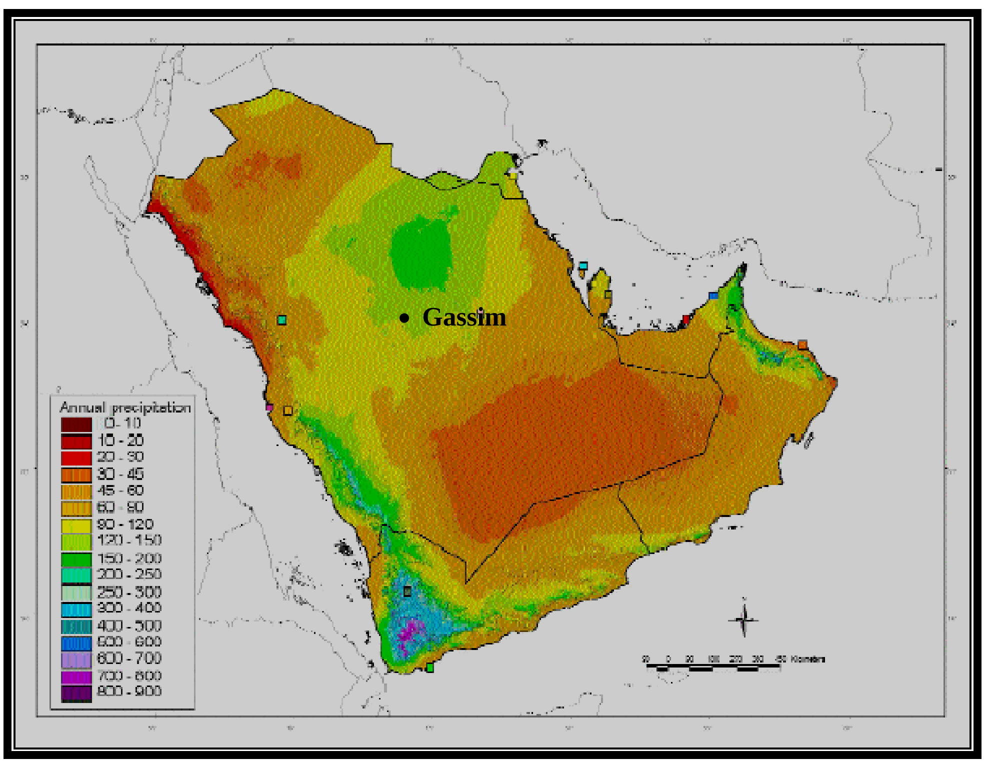


Figure 4.3: Average annual rainfall of Arabian Peninsula (Source: De Pauw, 2002).

4.2.2 Factors Affecting the Climate in Saudi Arabia

To understand the general climatic conditions of Saudi Arabia it is important to explore its main influences and these are reviewed in the following sections by season.

4.2.2.1 Winter

The climate in Saudi Arabia is subjected to various air movements over the year (Alyamani, 1993). In winter (December, January and February), Saudi Arabia is primarily affected by a Siberian high pressure system, which comes under the influence of a Continental Polar (cP) air mass that develops over Asia (Figure 4.4). This high largely prevails over winter, and is characterized by generally clear skies, dry air, and fairly low temperatures. At the same time, night air temperatures may drop to below 0°C, although daily air temperatures tend to be around 10°C, and the prevalent weather conditions are usually pleasant (Al-Blehed, 1979). The cP air mass starts to influence Saudi weather in the late autumn, when it begins to intensify and move southward. This causes a strong northerly surface wind which continues for a period of three to five days, and is particularly noticeable in northern, central and eastern Saudi Arabia (Hubert et al., 1983).

Saudi Arabia is occasionally affected by a low pressure system moving eastward, which normally comes under the influence of a succession of Maritime Polar (mP) air masses that develop over the North Atlantic Ocean. These air movements are the remainder of mid-latitude depressions that cross the Mediterranean and North Africa. As these systems move inland, cold frontogenesis takes place between the modified mP air transported eastward and the cP air moving southward behind the low (WWFM, 1986). This is the main source of winter rainfall in the country.

The Sudan Low, which develops over East Africa, also plays a role in winter by advecting warm humid air to the south-western parts of the country (Anbar, 2001)

(Figure 4.5). Finally, it should also be mentioned that the major factors controlling the average temperature in the winter period are latitude and elevation i.e. from south to north there is a clear cooling trend, owing to increased exposure to cold continental air masses in winter (Figure 4.6).

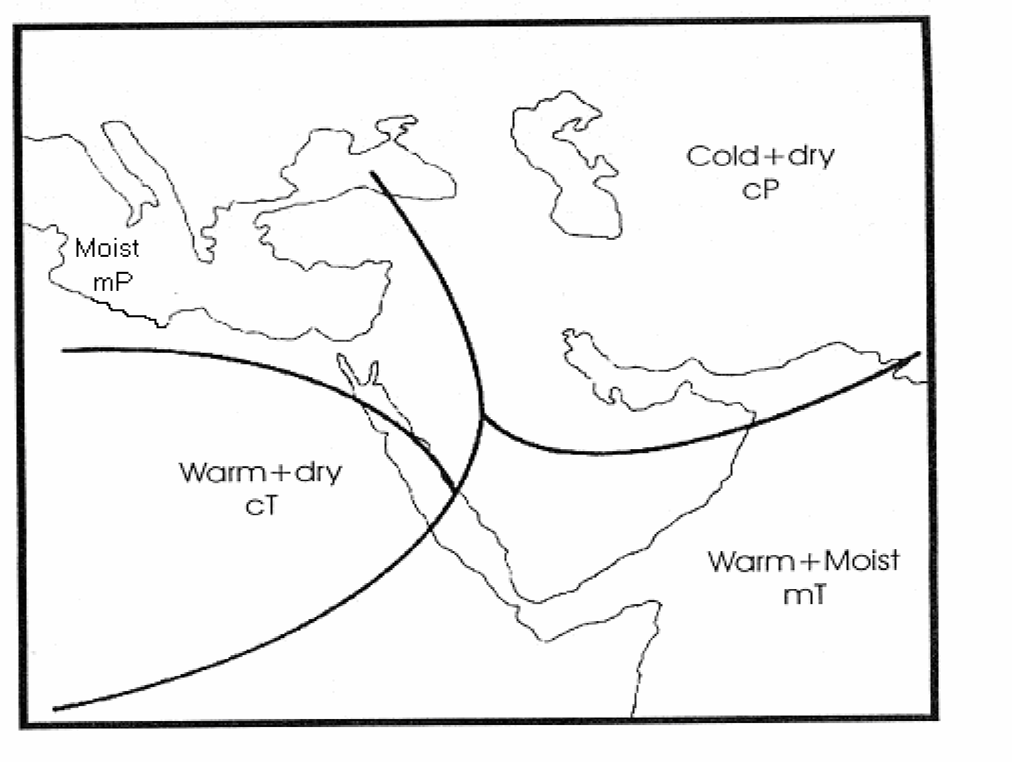


Figure 4.4: Air masses that affect the climate of the Arabian Peninsula in all seasons (modified from Al-Qurashi, 1981).

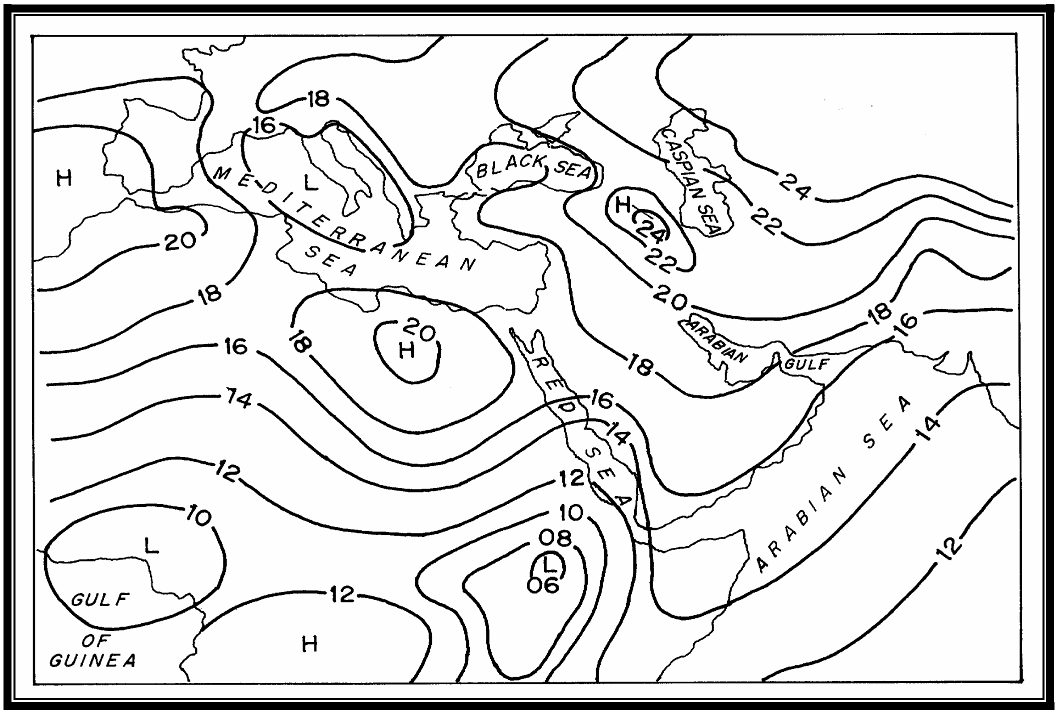


Figure 4.5: The distribution of average sea level pressure (mb) in winter. Units are in millibars +1000 (Source: Al-Qurashi, 1981). The last two digits of pressure in millibars are shown (e.g. 04 is 1004 and 96 is 996 mb).

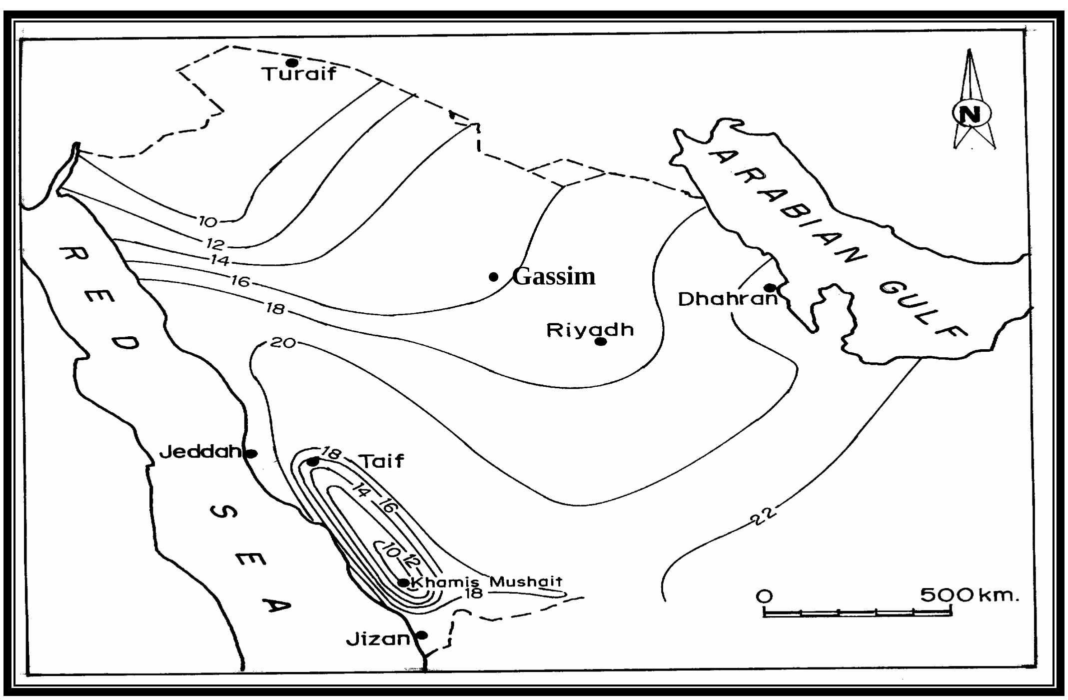


Figure 4.6: The distribution of air temperature (°C) in Saudi Arabia in winter (Source: Al-Qurashi, 1981).

4.2.2.2 Summer

During summer (June, July and August) Saudi Arabia is influenced by Continental Tropical (cT) air masses that develop over the Sahara in North Africa, Arabia, and northern India and Pakistan in Asia, and these bring hot and very dry air. The Indian Monsoon system affects south-western Saudi Arabia, as well as parts of Yemen and coastal Oman (Figure 4.7). However, its influence is limited by the strong Tropical Continental Air Mass, which prevails over the Peninsula at the time. These air masses allow the region to become a stable high-pressure zone and a source of tropical continental air (De Pauw, 2002). Finally, latitude is a major factor controlling average temperature in summer i.e. from south to north there is a clear cooling trend, owing to increased exposure to cold continental air masses (Figure 4.8).

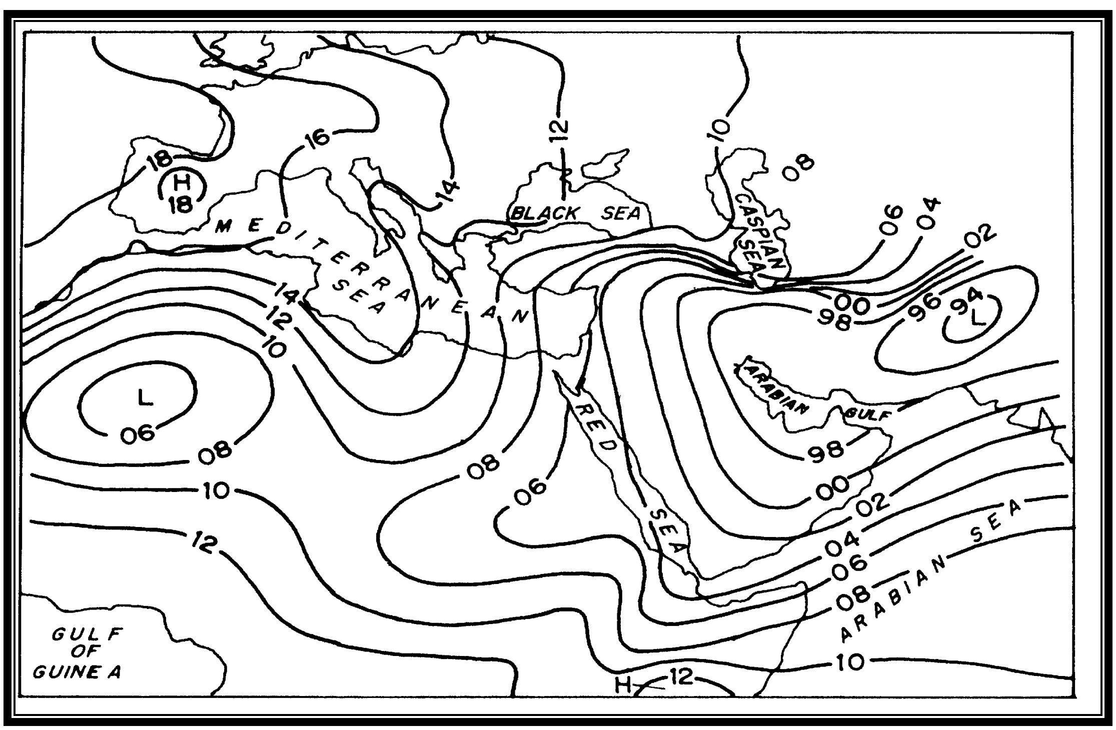


Figure 4.7: The distribution of average sea level pressure (mb) in summer (Source: Al-Qurashi, 1981). Units are in millibars +1000. The last two digits of pressure in millibars are shown (e.g. 04 is 1004 and 96 is 996 mb).

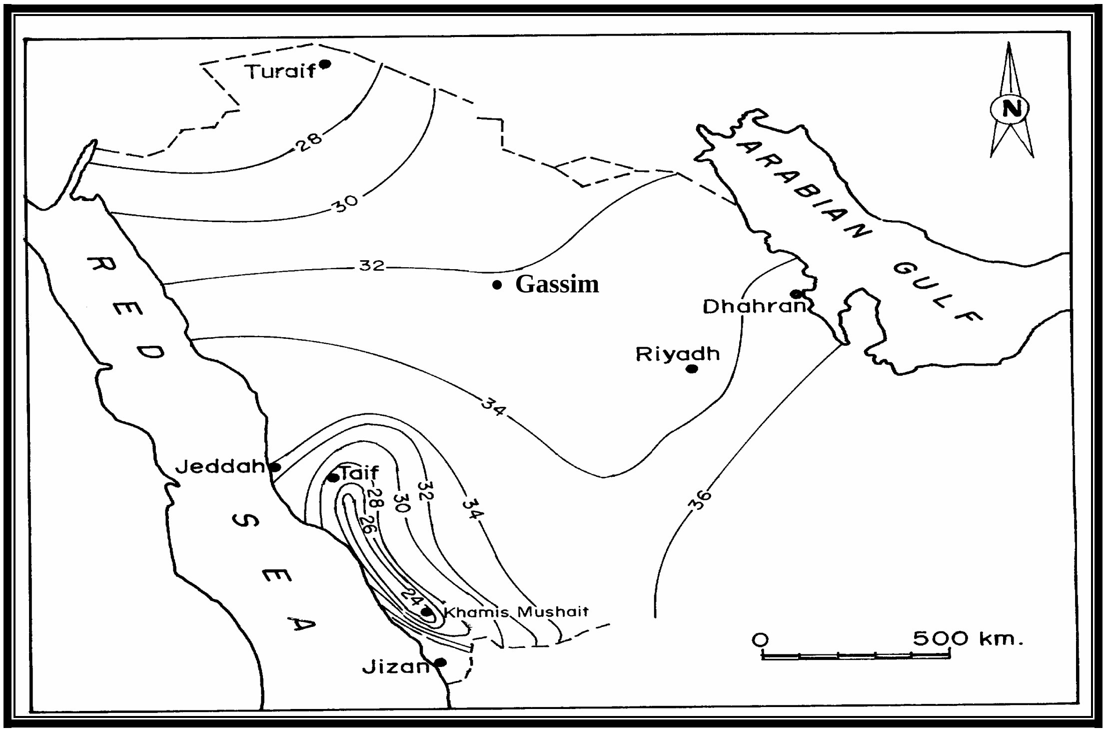


Figure 4.8: The distribution of air temperature (°C) in Saudi Arabia in summer (Source: Al-Qurashi, 1981).

4.2.2.3 Autumn and Spring

Autumn (September, October and November) is a period of transition. It begins with only slight variations from the summer features; there is a gradual flattening of pressure during early autumn, with light and variable winds. The Siberian high pressure begins its southward movement, and frontal systems appear in the east of the Mediterranean. The summer thermal low in the east of the Kingdom is gradually replaced by the winter ridge; and with the arrival of the first cold front, winter begins (MEMO, 1986).

During spring (March, April and May) the Siberian high pressure draws back, even though a weak ridge remains over the country. A trough, extending from India westward up to the Arabian Gulf, typical of summer conditions, begins to appear with local thunderstorms. The cT air mass continues to hold sway over the south and

south-west and throughout the spring season, dust, sand storms and dryness are the most noticeable characteristics of this cT. In addition, the Hobob / Khamsin wind, one of the local winds which is a very hot, dry, dusty, south or south-westerly wind, blows almost continually during this season (MEMO, 1982).

4.2.3 General Characteristics of the Climate in Gassim

The Gassim area is located between latitudes 24° 30’ and 27° 15’ N, and longitudes 41° 50’ and 44° 50’ E, in the centre of Saudi Arabia. It is thus broadly representative of the climate in most of the country’s regions. It is an arid zone, where the annual potential evaporation exceeds the rainfall. Gassim’s climate is characteristically continental with long, hot and dry summers, and short, cool winters.

The average monthly temperature, rainfall, relative humidity, wind speed, sunshine duration and potential evaporation, for the 30 year period 1971 to 2000 are plotted in Figure 4.9. These data originate from the Unizah station discussed in Chapter 3. Unless stated otherwise all averages presented are calculated for the full available record (1971-2000, except sunshine, 1976-2000).

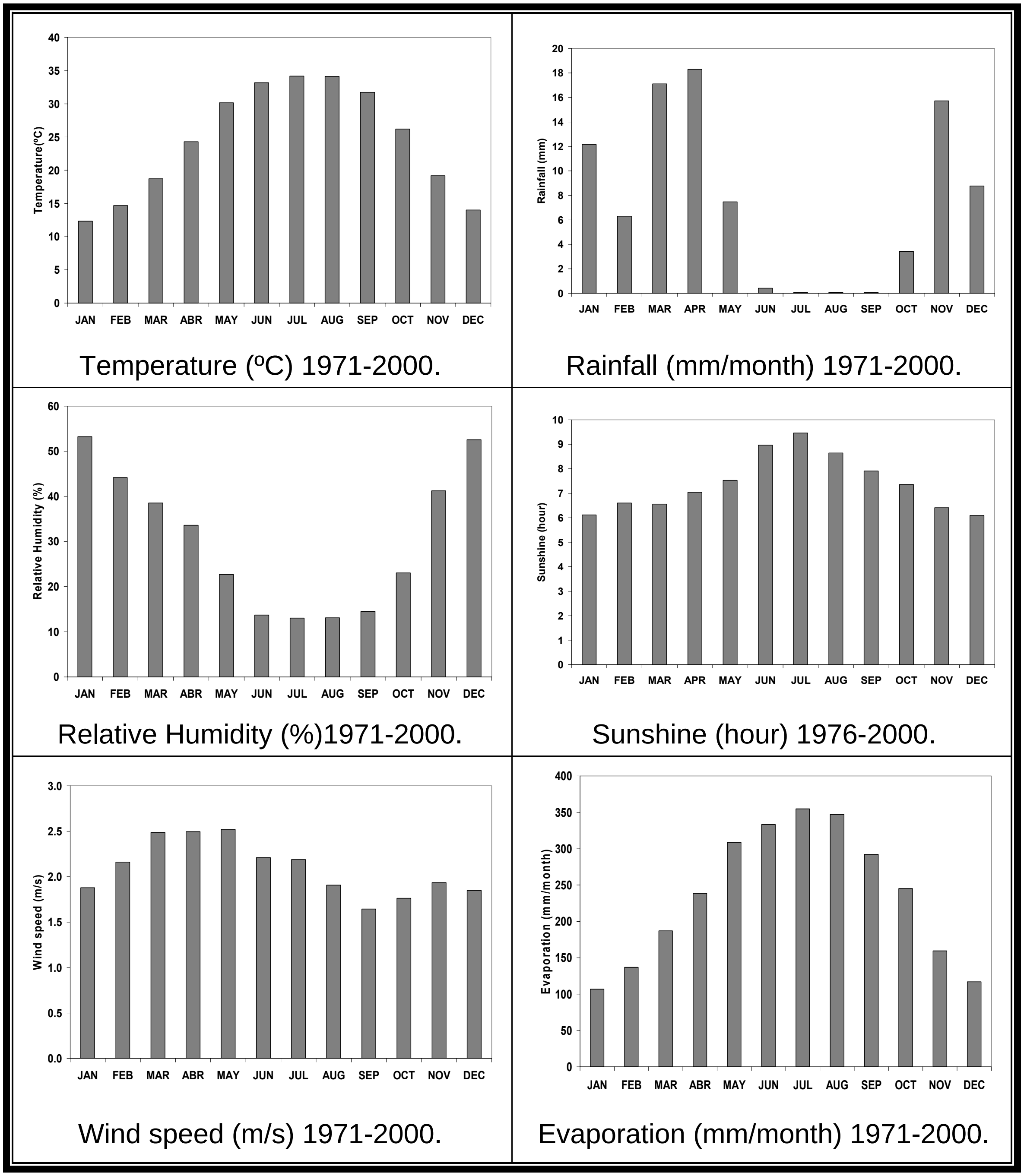


Figure 4.9: Average monthly climatic parameters for Gassim.

4.2.4 Seasonal Patterns in Air Temperature

The average annual temperature is 24.3°C. The annual air temperature range is defined as the difference between the average temperature of the coldest month and that of the warmest month. Typical of a desert, the annual range of temperature is normally about 21.3°C. In terms of the average DTR, for the winter month of January it is 12.1°C, and for the summer month of July it is 16.9°C.

The daily averages for all 365 days over 30 years are presented in Figure 4.10, for maximum, minimum, and average temperatures, DTR and the altitude of the sun's position. August is the hottest month and January the coldest month. Figure 4.10 also shows a decrease in temperature from August, through autumn to January, after which it gradually increases from February through the spring, reaching its maximum value in the summer. Temperature change during the year is almost precisely paralleled by the midday altitude of the sun's position. This is determined by latitude, which is perhaps the most significant control in the distribution of air temperature, as it determines the amount of heat received directly from the sun. In addition, maximum temperature is more changeable than minimum temperature during the year and their standard deviations are 9.4°C and 7.7°C, respectively. In terms of the DTR during the year, there is no significant change, although it is higher in summer than in winter. Air temperatures between November and April are generally pleasant, but from May to October they are considerably higher, necessitating the continuous use of air-conditioning inside buildings.

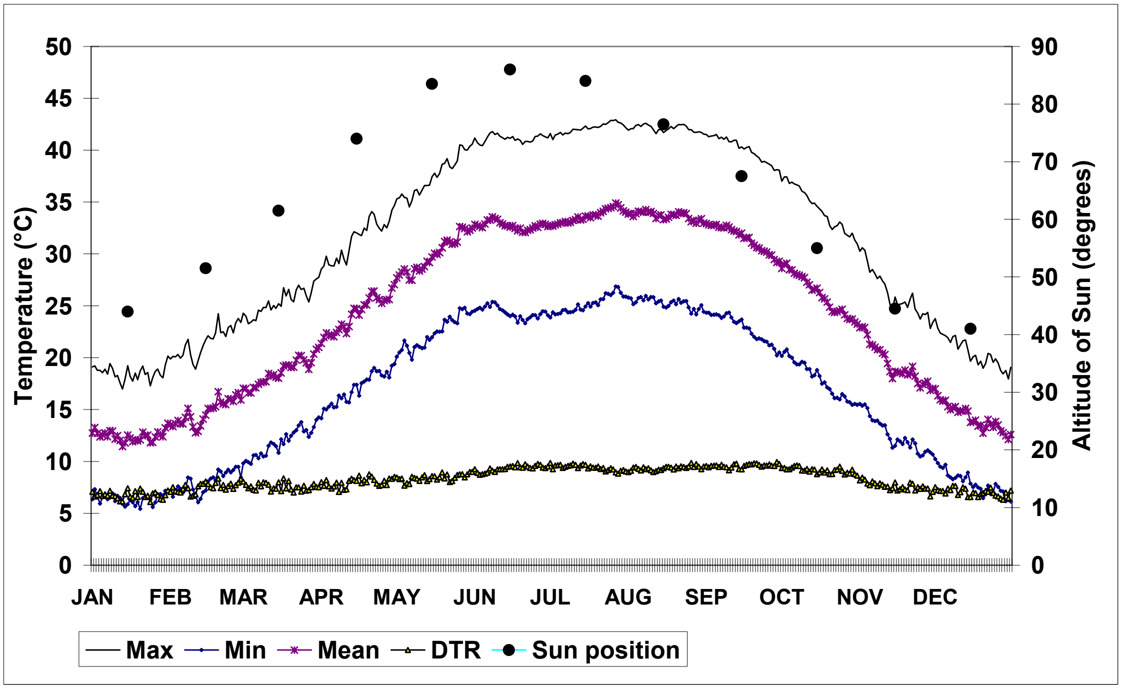


Figure 4.10: Average daily maximum, minimum and average temperatures, DTR, and the average monthly altitude of the sun at midday in the Gassim area (1971-2000).

Table 4.1 shows the seasonal and annual average values for temperature variables. The coldest month in the winter season is January, with an average temperature of about 12.4°C (Figure 4.9), as January temperatures are under the influence of the Continental Polar (cP) air masses. Therefore, from time to time, air temperatures can drop to below 0°C in the study area, and the lowest temperature recorded during the winter over these 30 years was -4°C in January 1992, when the DTR on that day was 12.4°C. The highest temperature recorded during this season was 35°C, which was recorded in February 1973, when the DTR was 20.9°C.

	Average seasonal temperature °C				Average annual
	Winter	Spring	Summer	Autumn	
Max	20.1	31.5	41.8	33.6	31.8
Min	7.4	17.1	24.9	17.8	16.8
Average	13.8	24.3	33.4	25.7	24.3
DTR	12.7	14.4	16.8	15.8	14.9
Standard Deviation	3.9	3.4	2.0	3.4	3.2

Table 4.1: Average seasonal temperature (°C) in Gassim from 1971-2000.

During spring the prevailing weather conditions have the characteristics of the winter season as the nights are temperate, and of the summer season as the days are relatively warm. The lowest temperature recorded in spring was 1°C in March 1992, (DTR on that day was 16.6°C). The highest temperature was 46.4°C in May 1982, (DTR was 22°C).

The summer temperatures are very high, the average is about 33.4°C. The dominant midday weather conditions are unbearable, with average maximum temperatures of 41.8°C with average minimum temperatures of 24.9°C (Table 4.1). The lowest recorded temperature was 12.8°C in June 1982 (DTR was 26.6°C). In contrast, the highest recorded temperature was 49°C in August 1998 (DTR was 20°C). The lowest temperature recorded during the autumn season over the 30 years was 2.5°C in November 1988, (DTR was 11.7°C). The highest temperature was 46.4°C in September 1999 (DTR was 17.8°C).

4.2.4.1 Recent Trends in Annual Temperature

Figure 4.11 shows a time series of annual average temperature which exhibits a marked positive trend of 0.5°C/decade. The temperature data show a warming of almost 0.37°C between the 1970s and the 1980s, and 0.73°C between the 1980s and the 1990s. The average rate of warming over this period is about 0.55°C per decade, and over all the average temperature increase in Gassim since 1971, is

about 1.5°C although the increase is not constant, with cooler years occurring in the early 1980s and 1990s (changes based on differences between decade – averages). This is higher than Qureshi (1994) found in the same area (0.8°C) and higher than the global trend of 0.6 ± 0.2°C since the late 19th or the beginning of the 20th century, up to 2000 (IPCC, 2001a).This rate is higher to average for east of Saudi Arabia, which has risen by 0.4°C (IPCC, 2001a, estimated from Figure 2.9 (d), value for East Saudi Arabia shown in Figure 4.12). During 1971-2000, the warmest year was 1999, (25.9°C), when the annual average air temperature exceeded the average by 1.5°C.

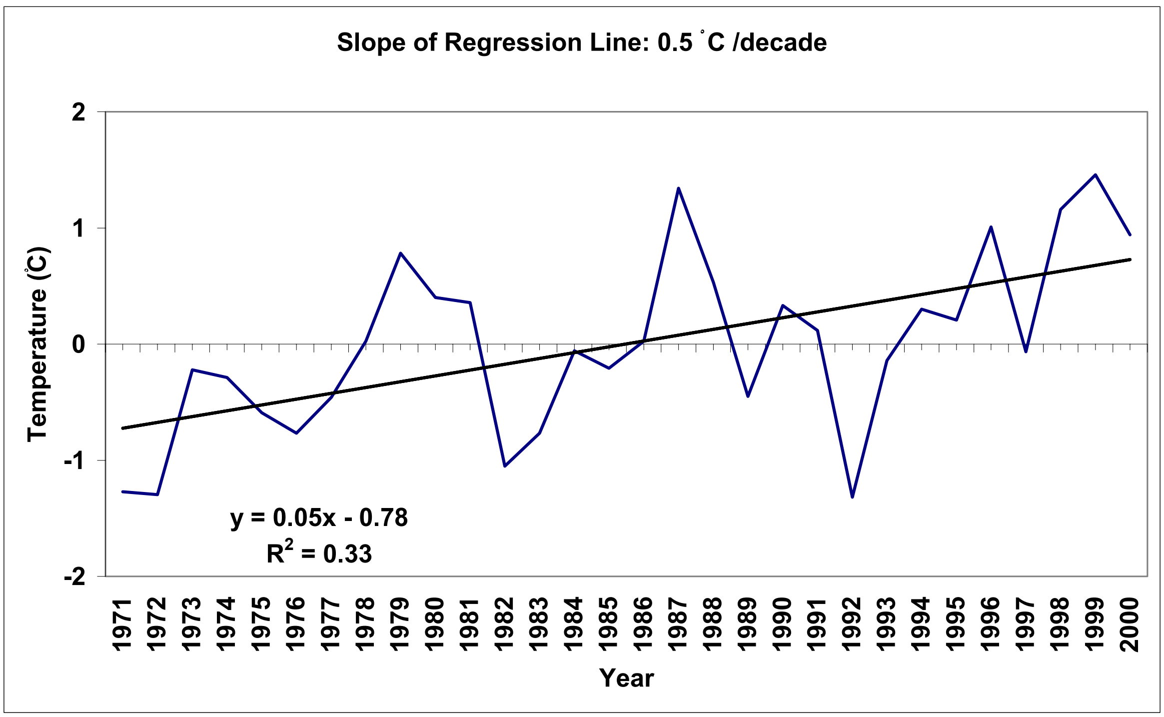


Figure 4.11: Gassim observed temperature expressed as anomalies from the 1971-2000 average. The solid black line is a linear trend line.

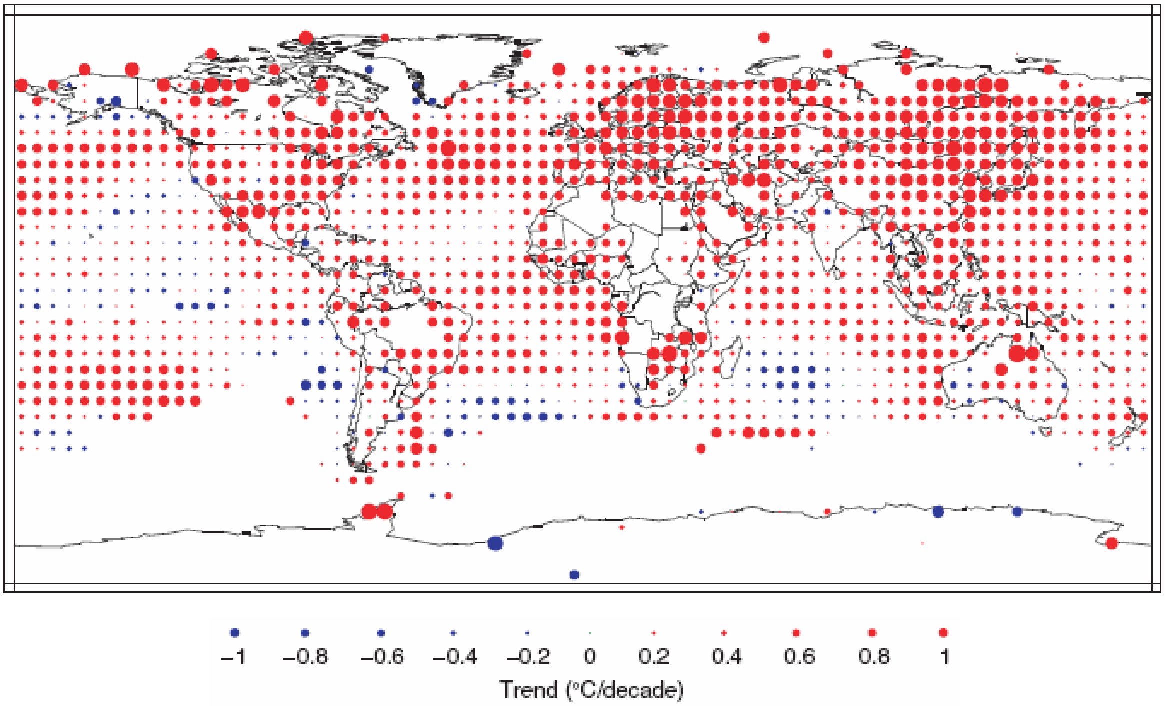


Figure 4.12: Annual surface temperature trends for the periods 1976 to 2000 (°C/decade). The red, blue and green circles indicate areas with positive trends, negative trends and little or no trend, respectively. The size of each circle reflects the size of the trend that it represents (Source: IPCC, 2001a, p. 116).

4.2.5 Recent Rainfall Variability

Data were obtained for eleven rain gauges (Figure 4.13) (daily) from 1971 to 2000 and provided by the MAW. Annual average rainfall is 92 mm, but there are differences between stations. Table 4.2 shows that the highest average annual rainfall is 113 mm, recorded at Dhala Rasheed, and the lowest average annual rainfall is 66 mm at Nuqra.

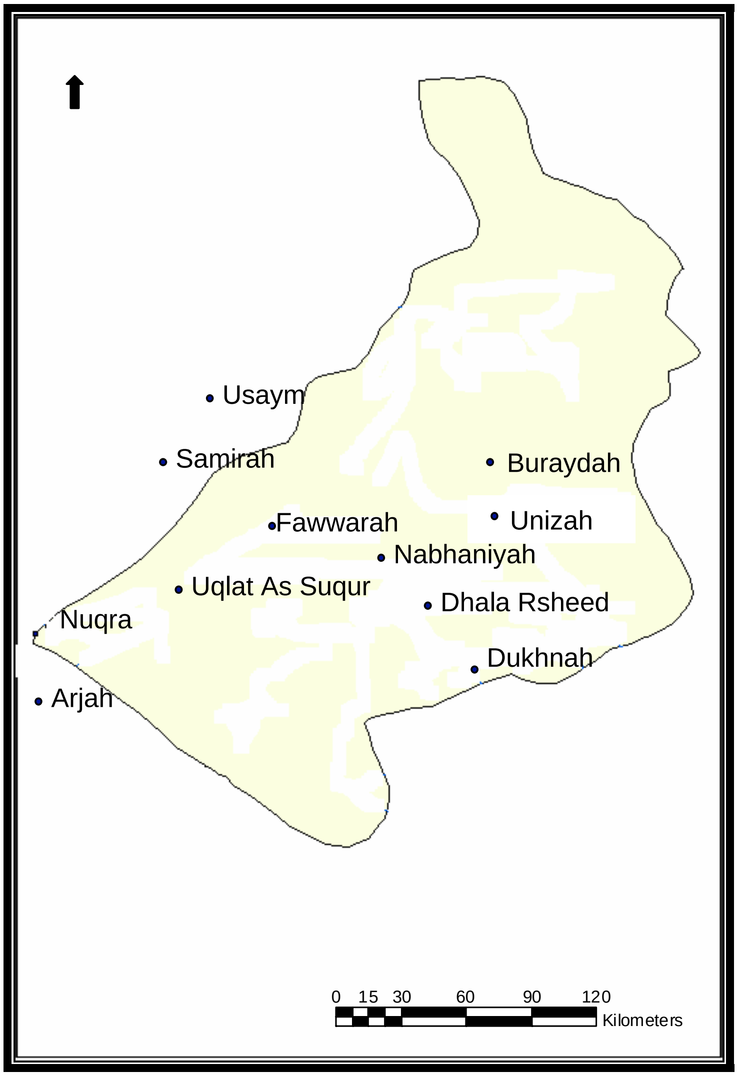


Figure 4.13: The location of rain gauges in the Gassim area.

Annual rainfall is generally significantly affected by elevation and other local factors. Elevation varies by only 410 m but as Figure 4.14a shows, there is no distinct relationship between elevation and rainfall in the area. In terms of latitude and annual rainfall, Figure 4.14b shows that the five most northerly rain gauges receive more rain than the others, except Dhala Rasheed. An explanation for this could be that the more northerly stations are located closer to the track of the Mediterranean depressions, although the physical distance between stations is not great (e.g. about 150 km from south to north). Figure 4.15 shows the differences in

annual average rainfall between the five northern rain gauges and the six southern rain gauges which are also similar. Although, it can be noted that the more northerly stations receive slightly more rainfall than the southerly stations (the averages are 101 and 84 mm, respectively).

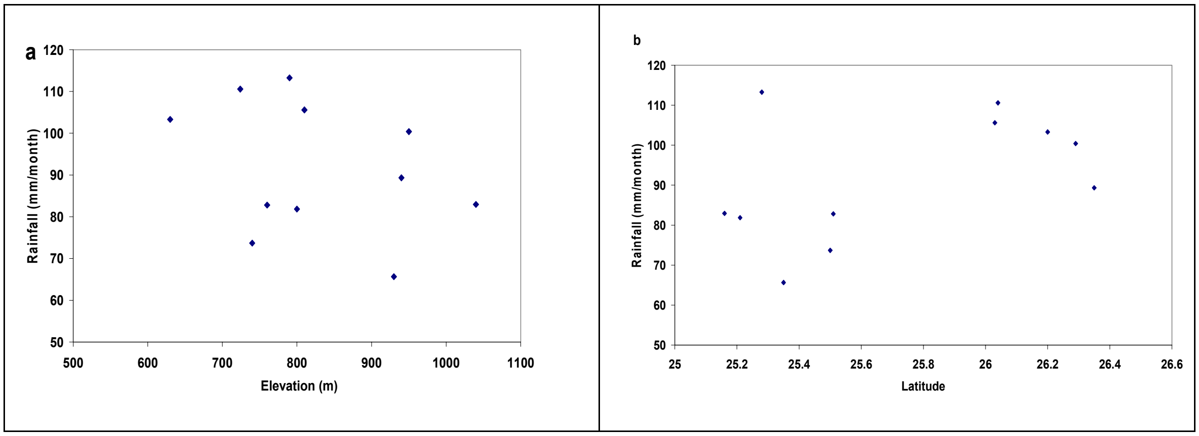


Figure 4.14: a,b: The relationship between annual rainfall, elevation and latitude for the eleven rain gauges.

Figure 4.16 displays the annual average (un-weighted) of the eleven rain gauges, and shows high interannual rainfall variability in the area. The range is very high 188 mm, the average is 92 mm and the standard deviation is 55 mm. The coefficient of variation of annual rainfall in the Gassim area is also very high (66%) likely influenced by three particularly wet years, 1972, 1976 and 1982. The linear trend of annual rainfall for the eleven rain gauges indicates a positive trend over the full period (3 mm/decade). The positive trend is also influenced by the occurrence of the three very dry years during the first part of the series and 1980 as well. Without these anomalous years, the rainfall regime has been fairly stable during the last 30 years.

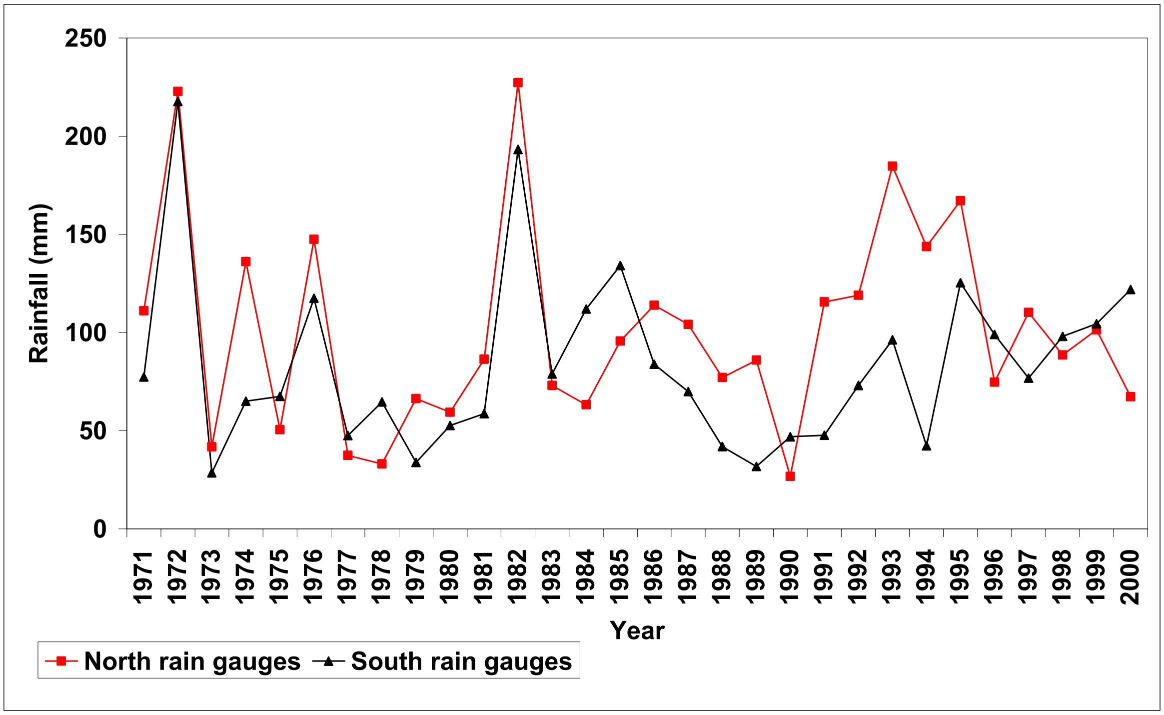


Figure 4.15: The differences in annual average rainfall between the five northern rain gauges and the six southern rain gauges in Gassim area, 1971-2000.

Generally, rainfall occurs between October and May, the seasonal rainfall totals are shown in Table 4.2. Spring is the main rainy season in the area, with 48% of the annual rainfall, followed by winter with 31%.

For the period of the summer, there are cloudless skies and the Gassim area is almost completely dry. Rainfall is less than 1 mm throughout the season, and the contribution to annual rainfall is only 0.6%. During autumn, the amount of rainfall is less than in spring or winter, but the variability is higher.

Table 4.2 shows that the annual rainfall coefficient of variation ranges from 50% to 79%, and the average is 65%. The trend of the eleven rain gauges ranges between -4 to 2.2 mm. Figure 4.17 also shows the number of rainy days; November has the highest daily rainfall intensity, but the highest number of days with rainfall occurs in April, although the total numbers are very low.

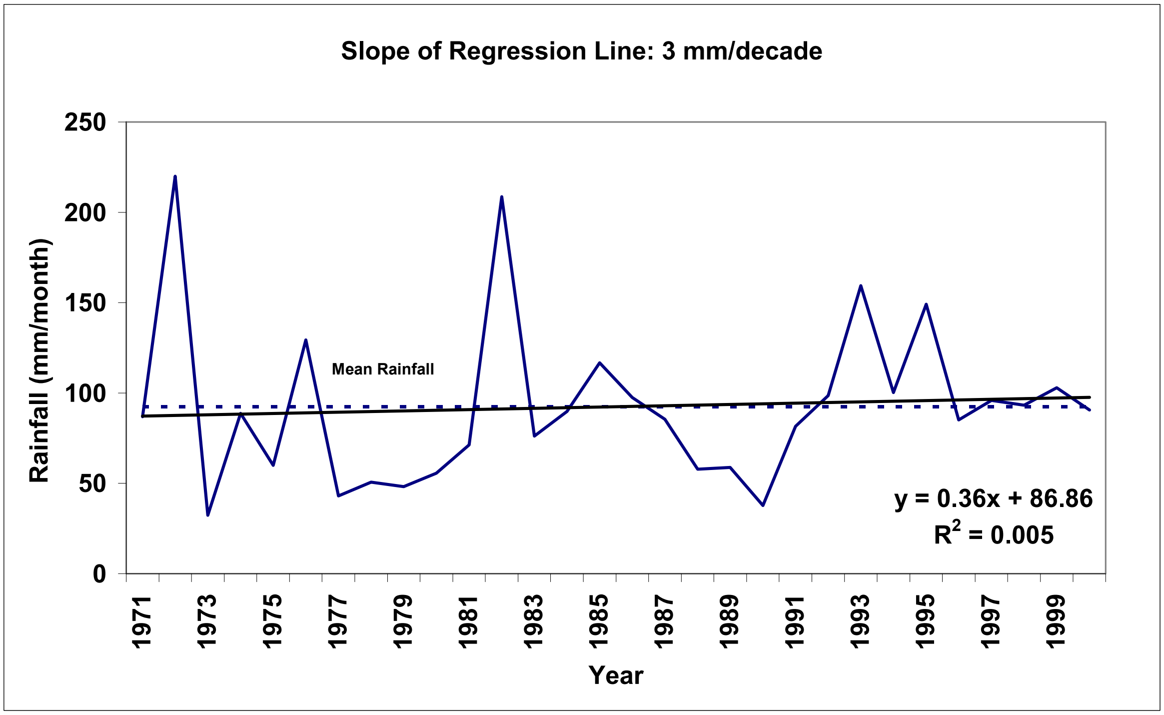


Figure 4.16: The annual average rainfall (eleven rain gauges) in the Gassim area, 1971-2000. Dashed line is long term average (92 mm).

	Rainfall stations											
	Usaym	**Unizah**	**Uqlat As Auqur**	**Samirah**	**Nuqra**	**Nabhaniyah**	**Fawwarah**	**Dukhnah**	**Dhala Rasheed**	**Buraydah**	**Arjah**	**Average**
Winter (mm)	30	37	22	36	16	25	33	26	35	33	19	28
Spring (mm)	39	56	35	43	31	48	53	36	56	53	36	44
Summer (mm)	1.4	0	1	0	1	0	0	1	0	1	1.4	0.6
Autumn (mm)	19	17	17	22	18	11	20	20	23	17	27	19
Annual	89	111	74	100	66	83	106	82	113	103	83	92
Std. Dev.*	62	73	54	68	48	66	58	61	56	60	53	60
C.V.**	70	66	73	68	72	79	55	74	50	58	64	65
Trend	-4	-1.4	-1.2	2.2	-2	-2.4	-0.5	-0.5	1.1	1.3	1.3	-0.6
Elevation (m)	940	724	740	950	930	760	810	800	790	630	1040	
Latitude	26.4	26.0	25.5	26.3	25.4	25.5	26.0	25.2	25.3	26.2	25.2	

Table 4.2: Rainfall characteristics for eleven rain gauges in the study area values

based on 1971- 2000.

*Std. Deviation of annual rainfall. **Coefficient of variation in %.

4.2.5.1 Daily Rainfall Characteristics

Table 4.3 displays the likelihood of a rainy day[1] during a year, expressed as a percentage, and these are very low, ranging between 2.3% and 4.9% with an average of 3.7%. Furthermore, Table 4.3 shows the average number of rainy days per year in the study area, (the average is 17 rainy days per year), with each rainy day receiving an average rainfall of about 5.7 mm.

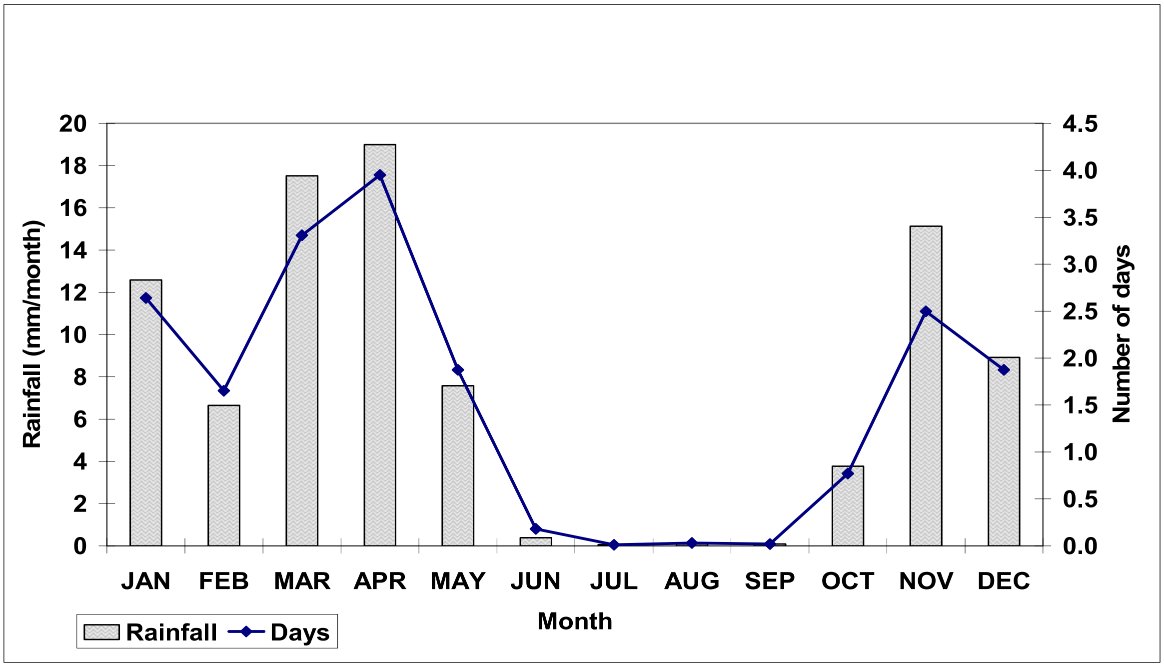


Figure 4.17: The average monthly rainfall in mm and the average number of rainy days for the eleven rain gauges in the study area.

[1] The definition of rainy day is any thing above 0.1 mm.

Station	Average number of rainy days per year		Average rainfall per rainy day (mm)
	Frequency	%	
Usaym	19.7	4.1	4.5
Unizah	26.2	4.3	4.2
Uqlat As Auqur	17.3	3.8	4.3
Samirah	14.9	3.8	6.7
Nuqra	15.2	3.6	4.3
Nabhaniyah	21.2	4.3	3.9
Fawwarah	13.0	3.6	8.1
Dukhnah	18.5	4.9	4.4
Dhala Rasheed	11.1	2.3	10.2
Buraydah	14.8	3.7	7.0
Arjah	16.2	2.8	5.1
Average	17.1	3.7	5.7

Table 4.3: Average number of rainy days per year, percentage probability of a rain day, and average rainfall per rain day for the eleven rain gauges.

4.2.6 Other Climate Factors

Four other climate factors; relative humidity, sunshine, wind speed and evaporation are also mentioned briefly because they are used in subsequent chapters to calculate ET_O. The seasonal patterns of each element are shown in Figure 4.9 (Section 4.2.3) and Table 4.4 for Unizah station. The average monthly relative humidity expressed as a percentage is 30.3%, where the driest month is July with 3%, and the wettest month is January with 53.2% (Table 4.4). Figure 4.18 shows that relative humidity has a negative trend with average rate of -1.8% per decade and the long term average is 30.3%.

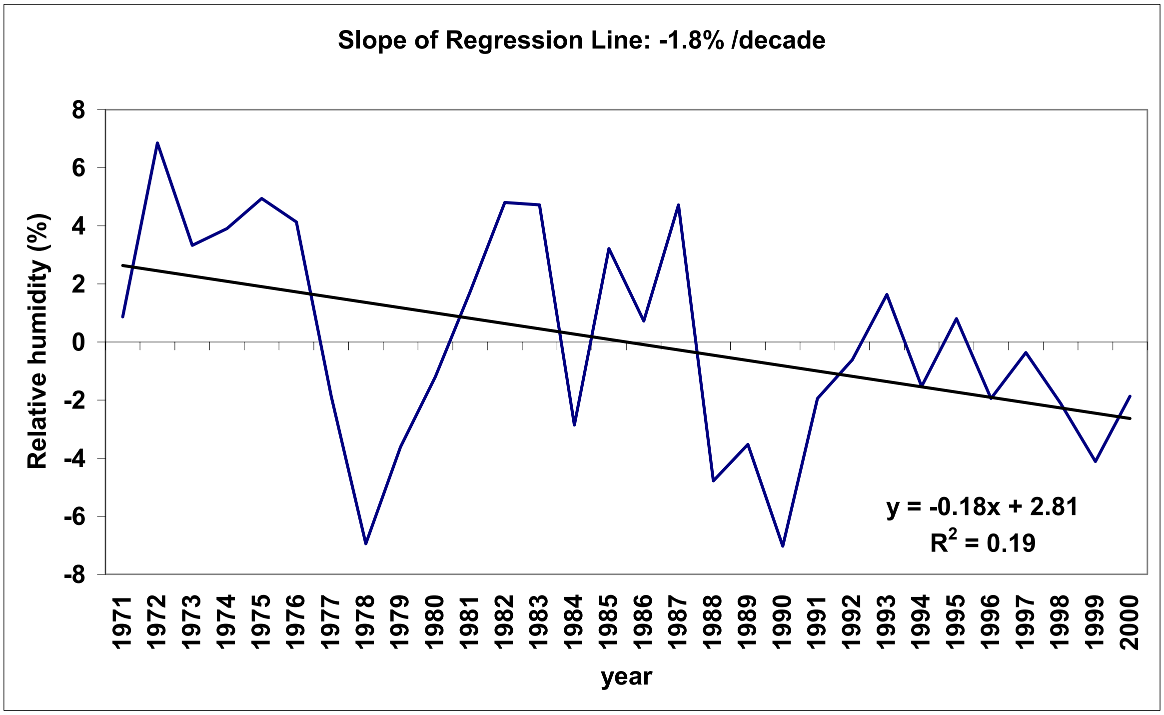


Figure 4.18: Gassim observed relative humidity expressed as anomalies from the 1971-2000 average. The solid straight line is the linear trend line.

The average monthly sunshine duration is 7.4 hours, peaks in July and is lowest in December and January (Table 4.4). Figure 4.19 shows that sunshine duration exhibits a negative trend. The rate of decline is highest during the early 1980s and the main period of decrease was from 1980 to 1985, whereas the trend from 1987 to 2000 was very stable. The explanation for the decline in sunshine duration is not obvious; it could be due to an increase in cloudiness and/or a possible increase in dust storm frequency (Qureshi, 1994).

The average monthly wind speed at 2 m height is 2.1 m/s. The average minimum and average maximum wind speeds over the 30-years period are 0.8 m/s and 3.8 m/s respectively. There is no long-term trend in wind speed (Figure 4.20). Finally, in terms of evaporation pan the average monthly value is 283 mm/month (Figure 4.9 and Table 4.4).

Parameters	Month												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ave**
RH (%)	53.2	44.2	38.5	33.6	22.7	13.7	13.0	13.1	14.5	23.0	41.2	52.5	30.3
Sun* (hour)	6.1	6.6	6.6	7	7.5	9	9.5	8.6	7.9	7.4	6.4	6.1	7.4
WS** (m/s)	1.9	2.2	2.5	2.5	2.5	2.2	2.2	1.9	1.6	1.8	1.9	1.8	2.1
Evap. (mm)	128	164	224	286	371	400	426	417	351	294	191	140	283

Table 4.4: Average monthly climatic parameters in the Gassim area (1971-2000).

* Sunshine, period (1976-2000).

**Wind speed.

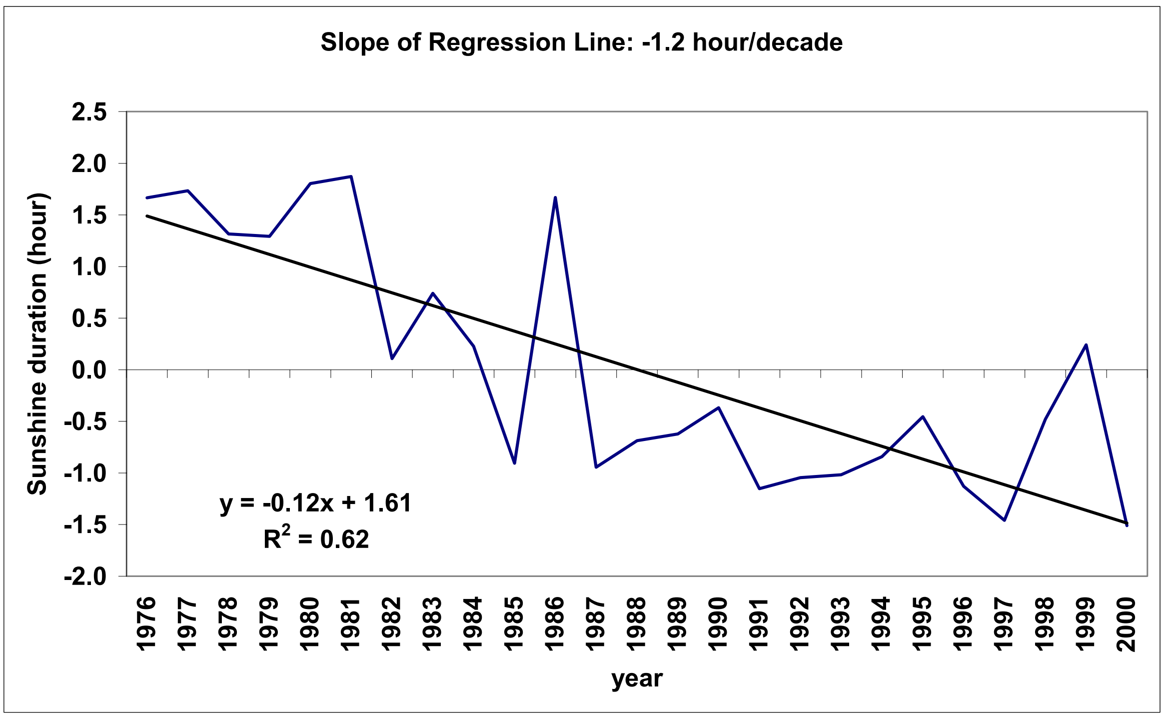


Figure 4.19: Observed sunshine duration expressed as anomalies from the 1976-2000 average, Gassim. The solid straight line is the linear trend line. The long-term average is 7.4 hours.

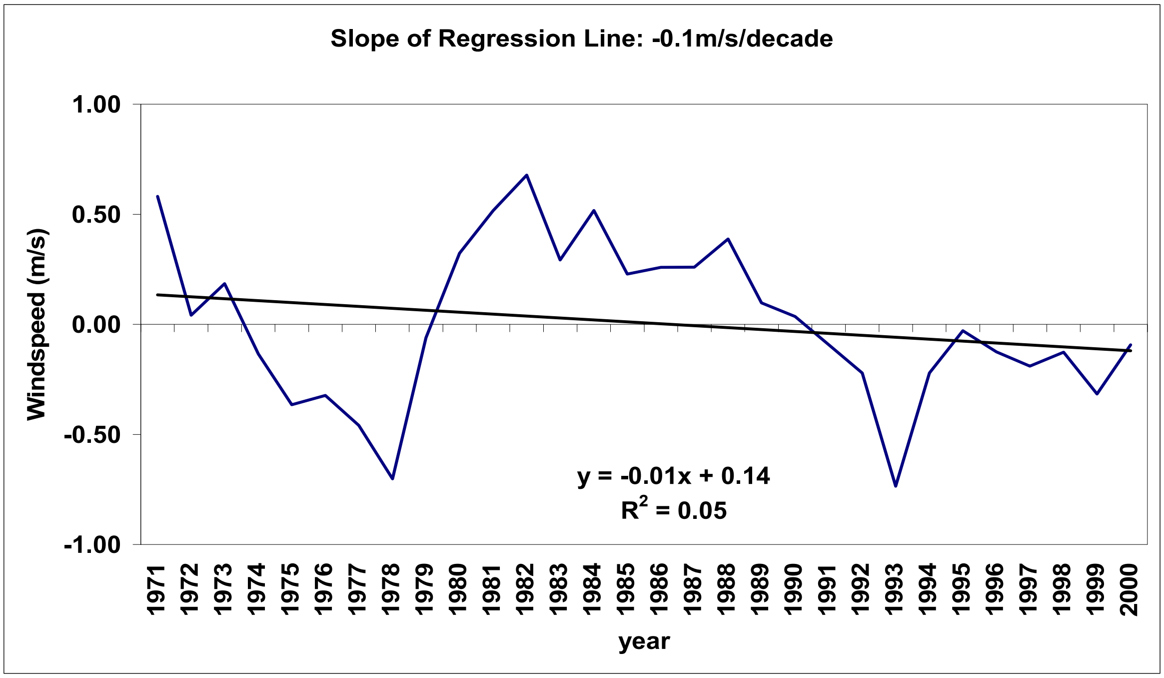


Figure 4.20: Gassim observed wind speed expressed as anomalies from the 1971-2000 average. The solid straight line is the linear trend line. The long-term average is 2.1m/s.

4.3 Water Resources and Water Use in Gassim

4.3.1 Introduction to Water Resources in Saudi Arabia

Saudi Arabia does not have any perennial surface streams in its 2.25 million km^2. On the other hand, Saudi Arabia is blessed with massive aquifers which are the source of large amounts of groundwater. These represent the main water sources in the country. According to the MAW, there are nine main deep aquifers; Wajid, Saq, Tabuk, Minjur, Biyadh, Wasia, Umm Er Radhuma, Dammam and Neogene, listed in order from the oldest to the youngest (MAW, 1984:). Al-Saleh (1992) indicted that his analysis of water samples from the above aquifers revealed water

ages of between 20000 and 30000 years B.P. These ages suggest that these are fossil groundwater resources, and therefore very precious and non-renewable.

Demand for water in Saudi Arabia is increasing dramatically as a result of high population growth, improved standards of living, and economic development, particularly in the agricultural sector (Figure 4.21). For example, the total water demand in 1980 was about 2.36 billion m^3 and one decade later it increased to 16.2 billion m^3. In 1995 the total water demand reached 18.2 billion m^3, with about 16.4 billion m^3 for the agricultural sector. The projected water demand for 2025 is estimated at 24.2 billion m^3 (Al-Naeem, 1999; Uitto et al., 1997). This massive increase in demand for water, especially for irrigation, has been reflected by declining levels of groundwater in most areas of the country (MAW, 1984). A particular concern is the enormous water demand for wheat which, since 1980, has increased rapidly on account of generous government subsidies. The government buys all wheat yields that are offered for sale by farmers at good prices in order to encourage wheat production (George, 1994).

The government has managed to halve its food imports and has become the world's sixth largest wheat exporter. This strategy has, however, significantly affected water resources, and has prioritised groundwater for wheat irrigation, resulting in the rapid depletion of a non-renewable resource. The issue of falling groundwater levels is becoming critical, and there are now increasing demands for wiser use of the limited quantity of water available. Saudi Arabia is using up its water resources over three times as fast as they are being renewed. Therefore, water tables have dropped dramatically across the country and readily available water resources could be exhausted within the next 20 years (Al-Attar, 2002), and according to the FAO (1997) within the next 25 to 30 years.

Because Saudi Arabia is under the water poverty line (1000 m^3/year per capita), with annual fresh water consumption per capita at 299 m^3 (Alrashed, 2004), and because water supplies in Saudi Arabia are under pressure, the government has

invested in desalination. This has been particularly so where groundwater depression occurs. The government was impelled to begin a desalination programmed in 1974, with the aim to become, by necessity, the world leader in the production of desalinated water for domestic consumption. There are now 7,500 desalination plants around the world, and 60% of which are located in the water-starved Middle East. Saudi Arabia alone has 25% of the global desalination capacity (Simmons, 2002). The combined capacity of the 28 desalination plants in the country has now reached 2.5 million m^3/day (Albayan, 2002), meeting 70% of Saudi Arabia's drinking water needs (Saudi Arabia Information Centre, 1996). In the light of these circumstances water is a key issue for policymakers, and may become much more of a serious problem in the 21st century.

In Saudi Arabia, all the water resources are owned by the government and policies are implemented through the MAW. The work of the Ministry is supported by several other governmental and semi-governmental entities such as the King Abdulaziz City for Science and Technology (KACST), the Saline Water Conservation Commission (SWCC) and Saudi Aramco. These organizations and many others deal with one or more aspect of water such as regulations, legislations and policies, research, water supply, distribution, protection. etc (Al-Shaibani, 2003). In relation to water use for agricultural irrigation purposes, each farm must obtain a licence from the MAW in order to gain access to groundwater and to dig wells. However, subsequent to the bureaucratic requirements being met, the MAW as owner allows all farmers to withdrew any quantity free of charge. Regarding the municipal purposes, the government sells one m^3 of desalinated water for as little as $ 0.5, whereas it costs $1.5 to produce (Alfagi, 2003).

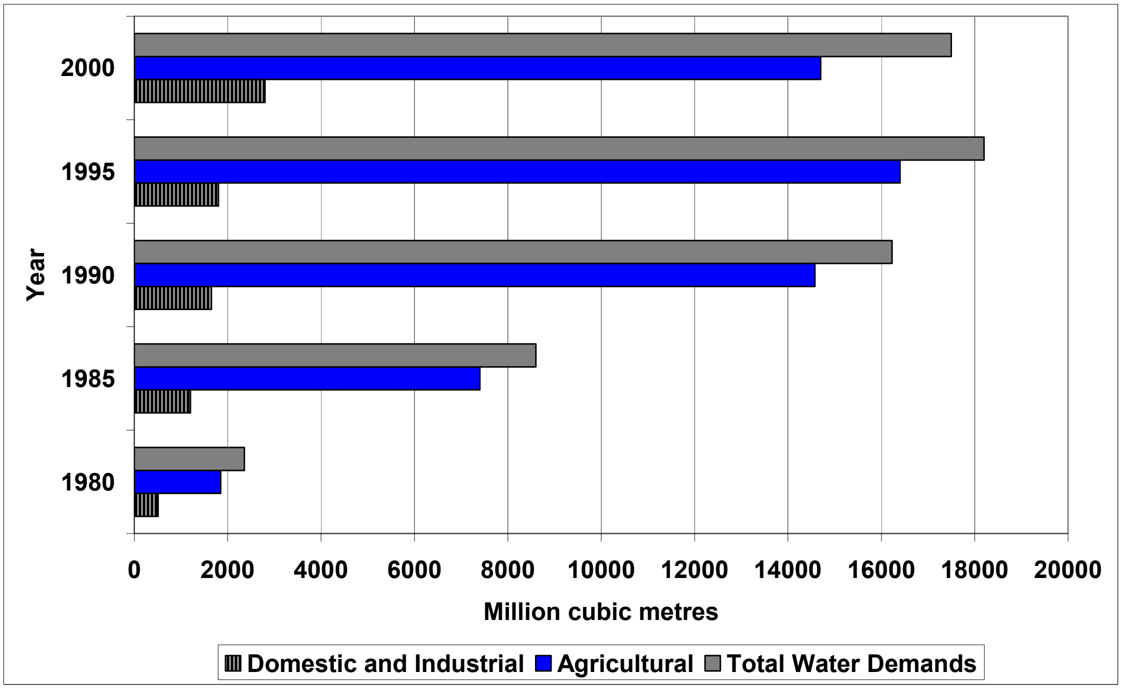


Figure 4.21: Water demand in Saudi Arabia. (Source Al-Naeem, 1999).

4.3.2 Groundwater Distribution in Gassim

Gassim possesses large reservoirs of groundwater; the area is located on the Najd plateau, gently sloping north-eastward, and is divided into two parts in terms of geology (Figure 4.22). The first is the western part, which consists of igneous and metamorphic basement rocks known as the Arabian Shield, and this contains limited renewable groundwater resources (Alwelaie, 1996). The Arabian Shield covers about 50% of the area and represents the lesser portion in terms of population, economy and agriculture. The second, and more important area, is the eastern part, which consists of a sequence of sedimentary layers known as the Arabian Shelf. This contains several layered principal and secondary aquifers, formed mostly of limestone and sandstone, and most of the agricultural activity is in this part.

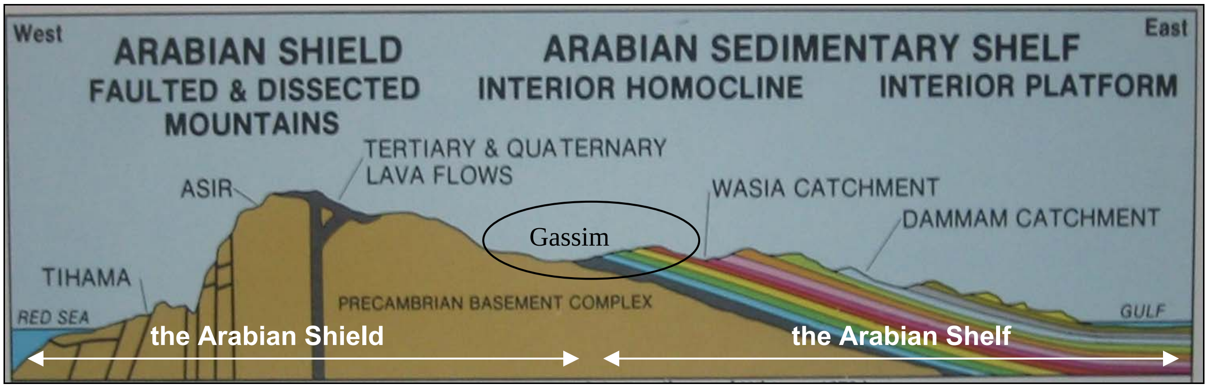


Figure 4.22: Generalized geological section of Saudi Arabia (modified from MAW, 1984).

Both of these types of groundwater aquifer are deep rock aquifers and are generally between impermeable strata except where they outcrop, they are large in area and contain mainly fossil groundwater (Beaument, 1981). On the Arabian Peninsula as a whole, the deep groundwater store is estimated at about 2,300 billion m^3, (Burdon, 1973; Edgell, 1997). Edgell (1997) indicated that the groundwater resources in these aquifers have existed since a palaeo-recharge period about 20,000 to 28,000 years ago. This suggests that most of the water in these aquifers accumulated during the wetter climatic phases of the Quaternary period (Al-saleh, 1992).

In the study area there are five aquifers, three of which are primary aquifers, where the majority of fossil groundwater is stored. These aquifers range in geological age from Cambrian to Tertiary, and all of them are predominantly sandstones of the Paleozoic and Mesozoic eras (MAW, 1984). These aquifers are all listed in Table 4.5: (Norconsult, 1984; MAW, 1984 and Abdulrazzak 1995)

1. The Saq Sandstone formation is the main aquifer, and supplies most of the wells in the study area. It has been estimated that 80% of the water used in Gassim is drawn from the Saq aquifer, and that 95% of this water is used only for irrigation purposes. The Saq aquifer in the area lies along the

northern and north-eastern margin of the Arabian Shield, and its age ranges from Cambrian to Ordovician. The vast outcrop of the Saq extends in to Saudi Arabia for about 1200 km; the area of its surface exposure is about 65000 square km, but its subsurface area is about 160000 square km. In the area of Gassim, the thickness of the Saq ranges from 400 to 700 m and the reserves are about 277 billion m^3.

2. The Tabuk formation, which is considered to be of the Ordovician and Silurian age, is an outcrop covering about 100000 square km. The Tabuk formation appears in many regions of Saudi Arabia, but in the Gassim area, the thickness of the formation only reaches 930 m and its reserves are about 205 billion m^3.
3. The Minjur Sandstone is dated as Late Triassic. The outcrop of Minjur is a narrow band, 10 to 33 km wide, and extends for 820 km. The thickness of the formation reaches 315 m and its reserves are about 182 billion m^3.

In terms of the secondary aquifers in the study area, there are two aquifers which are important sources of water locally and these can be described as follows:

1. The Khuff Formation has an outcrop extending for about 1200 km, the width of which is about 25 km. The formation ranges from 235 to 300 m thick in the study area and its reserves are about 30 billion m^3.
2. The Jilh Formation, which is Middle Triassic, has an outcrop extending for about 770 km, the width of which ranges from 8 to 20 km. The thickness of the formation reaches 326 m and its reserves are about 113 billion m^3. (MAW, 1984 and Abdulrazzak 1995).

Aquifer	Age	Reserves
Saq Sandstone	Cambrian to Ordovician	277 billion m^3
Tabuk	Ordovician and Silurian	205 billion m^3
Minjur Sandstone	Late Triassic	182 billion m^3
Khuff	Permian	30 billion m^3
Jilh	Middle Triassic	113 billion m^3

Table 4.5: The main deep aquifers in Gassim area.

There is an other type of aquifer in the area; alluvial aquifers, which represent a shallow groundwater system. Groundwater in these aquifers is a renewable resource and is very sensitive to rainfall. The thickness of these alluvial aquifers generally ranges from 20 to 200m, and their widths are from a few hundred metres to several km (Abdulrazzak, 1995). Groundwater from the shallow aquifers in the study area is utilized mainly for domestic and irrigation purposes.

4.3.3 Groundwater Abstractions

Many current patterns of water withdrawal from groundwater in the study area can be considered unsustainable. The irrigated area in Saudi Arabia has increased from about 0.4 million hectares in 1971 to about 1.62 million hectares in 1992, which represents a 305% increase (El-Arnin et al., 2003). For an illustration of scale, in Saudi Arabia there are about 45 large irrigation schemes, each utilizing between 50 and 500 wells to irrigate from 5000 to 35000 hectares. Total irrigation water consumption per year has increased from about 1850 million m^3 in 1980 to about 16.50 billion m^3 in 1995 (Figure 4.21). The enormous water demand for irrigation is based on Saudi government policy of self-sufficiency in food and sadly, on the use of non-renewable groundwater for growing wheat and other crops, which generally requires 2000-3000 tons of water per ton of grain (Akkad, 1990; Uitto et al., 1997)

The costs of water are currently very low; about SR 0.23 ($0.06) per cubic metre (Al-Naeem, 1999). Such low water costs may encourage careless use of water, thereby potentially increasing the utilization of the limited groundwater resource, although some excess water may be returned through percolation (see Section 5.12).

The eastern half of the Gassim area has a network of observation wells, which were installed by the MAW in the mid-1960s to monitor groundwater levels. It was not possible to obtain full data on groundwater withdrawals and levels for the area. However, some data were available for five wells in the area of Gassim, but only from 1997 to 2001. Additionally, the MAW contributed a report to the Water Atlas of Saudi Arabia (1984) on trends in groundwater levels, where they presented some well series in Saudi Arabia from 1979 to 1982, and fortunately, one of these wells is one for which the present study has data for 1997 to 2001. Therefore, it was possible to make comparisons between the two periods for one well (Well 5 in the Saq Aquifer).

Figure 4.23 shows groundwater levels for Well 5 in the Saq Aquifer. The series shows a strong negative trend in groundwater levels. The two arrows in Figure 4.23 indicate missing data from 1983 to 1996. It is important to emphasize that the pumping of large quantities of water from this aquifer, has caused the level to fall by about 71 m over 23 years. This suggests that the massive use of irrigation water has lead to a decline in groundwater level by about 3 m per year in this well. This rate is similar to that in the Al-Hasa, southeast of Gassim, where the rate of decline is about 4 m per year (Asharq Alawsat, 2004). However, the rate of decline is not constant and it can be noted that from 1997 to 1999 there was a slight increase.

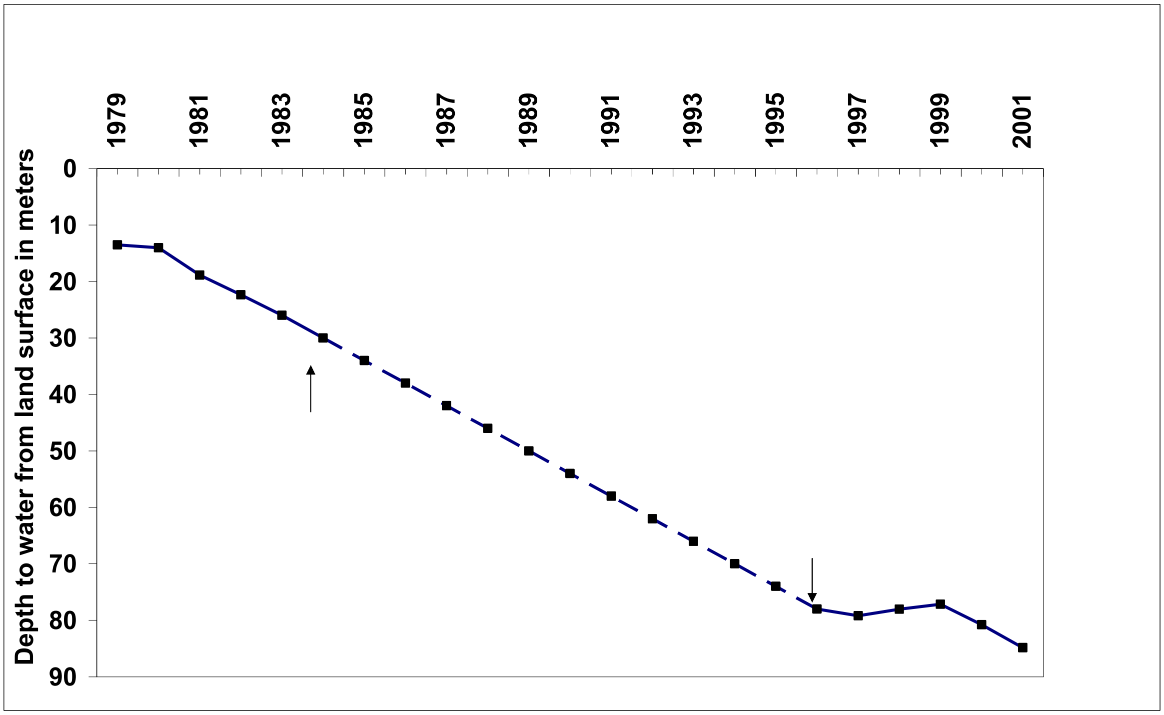


Figure 4.23: Changing water levels over time in Well 5 of the Gassim area from 1979 to 1982 and 1997 to 2001 (The two arrows indicate missing data from 1983 to 1996).

Figure 4.24 shows monthly groundwater levels in five wells in the area. These oscillate in reaction to changes in the quantity of water stored inside the aquifers, in much the same way as the water level in an aquifer reservoir fluctuates with storage changes. Consequently, Figure 4.24 shows that the groundwater levels in Wells 2, 3, and 5 tend to decline when abstraction exceeds recharge, but tend to rise when recharge exceeds abstraction during the winter when the aquifer is replenished by annual rainfall. Beaument (1981) and Pike (1983) indicted that a recharge of these aquifers is currently taking place at an estimated 15% of the annual rainfall. In addition, Al-Naeem (1999) reported that in the Hail area, which is located in the northern part of the Gassim area, the annual recharge over the outcrop area of the Saq aquifer is 6 mm/year; this comprises about 5% of the average annual rainfall.

It is clear that groundwater levels in the five wells have decreased over the five years, by between 5 and 12 m from 1997 to 2002. However, the MAW (1984, p.65) reported that:

> *''Any change of water level in a single well does not necessarily indicate uniform changes throughout an aquifer. Thus, the fact that water levels are declining in one aquifer in one specific location does not necessarily indicate that a serious overdraft problem exists''.*

Nevertheless, water levels in the aquifers have fallen in many areas, especially in the study area (Al-saleh, 1992). Indeed, the Ministry of Planning (1990, p.171) reported that:

> *''Annual water extraction of non-renewable groundwater has increased more than tenfold, mostly because of the rapid expansion of agriculture, and of wheat production in particular. This high growth rate in wheat production has been closely linked to high depletion rates of non-renewable water resources.''*

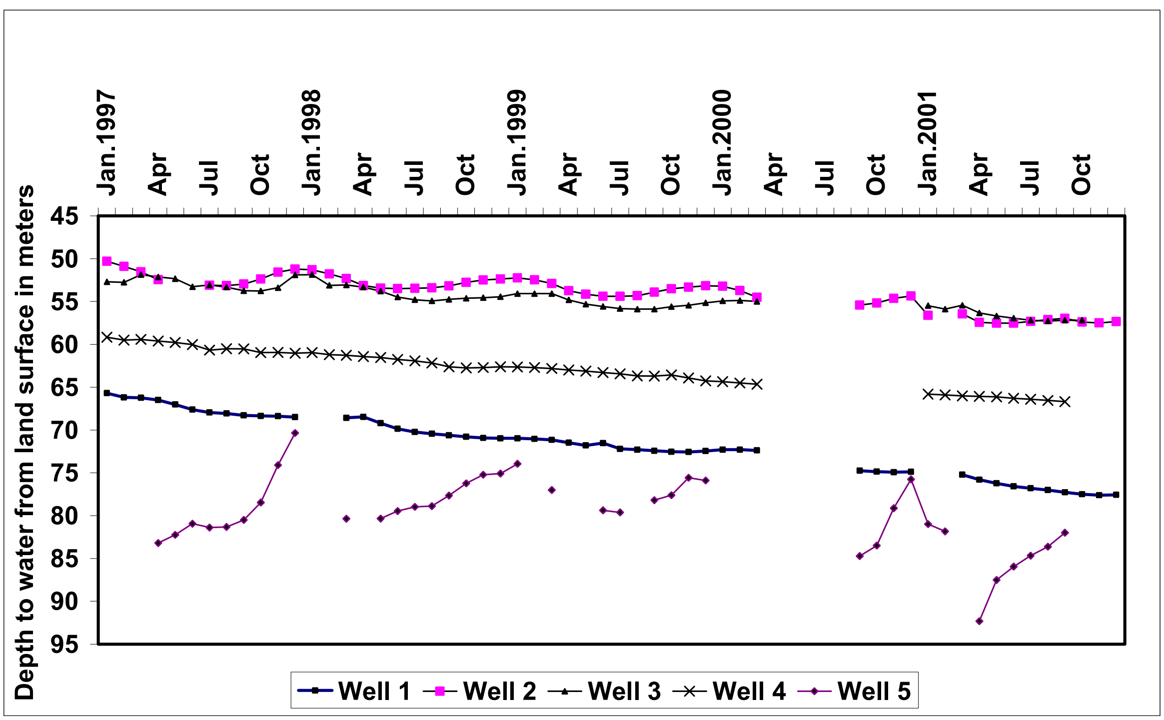


Figure 4.24: Changing water levels over time for five wells in the Gassim area, from 1997 to 2001. (The gaps are missing data).

Many foreign experts have estimated that there are only 15-20 years of water resources remaining (George, 1994). The main concern has been about declining water tables, Lake Layla was the largest permanent natural lake in Saudi Arabia (about 2 x 0.75 km), on the edge of Rub Al-Khali (the Empty Quarter) (Jones, 2005), approximately 700 km south of Gassim. The water level of Lake Layla began to decline in the early 1980s, in synchronization with the agricultural boom in Saudi Arabia. Jones (2005) indicated that by 1989 Lake Layla dropped by almost 20 m and that by the mid-1990s there was only a metre or so of water left. This was a dramatic 35-40 m decline in the water table, and by 1997 it was completely dry and totally disappeared (Picture 4.1).

4.3.4 Groundwater Quality

Along with declining levels, groundwater quality is also an issue of some concern in the study area, Al-Sagaby (1999) investigated water chemistry in the Saq aquifer in central Gassim, comparing two data sets from different sampling times. The first measurements were made in 1985 and the second in 1996. The results revealed that salinity in the study area had increased by 21% over the average salinity in 1985. In addition, Shafik et al. (1997) investigated 217 representative water samples in the Gassim area, and their results revealed that the salinity of irrigation water (ECw) was in the range of 0.33 to 12.81 mmhos/cm, with an average of 3.71 mmhos/cm. Thus the water salinity ranged from 210-8200 ppm with an average of 2375 ppm. Note for this research water samples were taken directly from the pumps on the case study farms during the fieldwork phase in 2003. The results show that the salinity of irrigation water (ECw), ranges from 0.7 to 14.0 mmhos/cm with an average of 8.4 mmhos/cm (see Section 5.6).

In view of the increasing salinity of the Gassim groundwater aquifers, Moghazi et al. (1999) reported a randomized survey based on 310 deep wells in 137 farms.


The blue water that filled the lake in 1980, before the expansion of wheat production.

The result of less than one decade, in 1989

The result of more than one decade, in 1996

Now Lake Layla has completely disappeared.

Picture 4.1: The story of how Lake Layla in Saudi Arabia simply disappeared (Source: Jones, 2005).

Their study showed that there is an average ratio of abandoned wells to the total number of wells as high as 22% and that this is due to the increasing salinity of the Saq aquifer. In addition, an analysis of 150 water samples showed that the total dissolved salts (TDS) had reached 2200 mg/L in 29% of the farms. They attributed this to holes found in the casings of the pumping wells, through which highly saline water enters from the upper aquifers. Groundwater quality will be considered further in Chapter 5 as an important factor in irrigation water use.

4.3.5 Dams and Reservoirs

By 1999 the MAW in Saudi Arabia had constructed more than 190 dams in different areas with a combined storage capacity of approximately 475 million m^3 in order to increase groundwater recharge and to help protect plantations and villages against the threat of flooding (Abdulrazzak, 1995). The larger dams, such as those in Wadi Jizan (storage capacity of 75 million m^3) Wadi Fatima (storage capacity of 20 million m^3), and in Najran (storage capacity of 85 million m^3), supply irrigation water for thousands of hectares of cultivated land. The second largest dam in the Middle East is Wadi Bisha dam, which is located in the south-western region of the study area and has a capacity of 325 million m^3 (FAO, 1997 and Saudi Arabian Information Resource, 2004). This supplies water for both agricultural and urban use. In Gassim there are four main dams, the biggest is for flood control and the rest are for aquifers recharge. The total storage capacity in 1995 reached 3 million m^3 (Ministry of Higher Education, 1999)

4.4 Conclusions

The present chapter has provided a description of the climate of Saudi Arabia and an analysis of recent climate variability in Gassim. The annual temperature range in Saudi Arabia is large (~20°C) and the total rainfall is approximately 100 mm/year. Many different factors affect the Saudi climate, e.g. elevation and latitude, and the seasonal interplay of regional air masses. The climate and recent variability in Gassim itself can be summarized as follows:

1. The average annual temperature in the study is 24.3°C, and the annual temperature range is about 21.3°C. August is the hottest month and January is the coldest.
2. In the summer season, the average DTR is 16.8°C, which is the highest value for the four seasons.
3. The average rate of warming over the last 30-years has been about 0.55°C per decade.
4. The average annual rainfall is 92 mm; the highest average annual rainfall out of eleven rain gauges is 113 mm, and the lowest is 66 mm.
5. Rainfall is concentrated between October and May, and the spring season is the main rainy season in the study area.
6. The average number of rainy days per year in the study area is only 17 and the mean wet day amount is 5.7 mm.
7. There is a slight positive trend in rainfall over the full period, the average rate of increase is about 3 mm/decade.

The second aim of this chapter was to investigate groundwater and water use in the area of Gassim and more widely in Saudi Arabia. The main findings can be summarised as follows:

1. The hot dry climate of Saudi Arabia heavily influences water demand for domestic purposes, and especially for agricultural purposes. This is especially

so in the light of the currently high rate of population growth, improved standards of living and recent economic developments, particularly in the agricultural sector. The total water demand in 1980 was about 2.36 billion m^3, only one decade later that value reached 16.2 billion m^3, and in 2000 it reached 17.5 billion m^3.

2. Two types of groundwater aquifer have been identified in the study area; principal aquifers, of which there are three, and secondary aquifers, of which there are two. Both types of aquifers are fossil groundwater.
3. There has been a 71 m decline in the water level in Well 5 over a 23 year period. In Wells 1, 2, 3 and 4 the water levels have declined by between 5 and 12 m from 1997 to 2002. If pressure on the water supply remains at this level, the Government may face very severe shortages, both in agricultural production and in water supplies.
4. Water quality in the Gassim area is likely to decrease with time; the salinity in the study area has already increased by 21% according to Shafik et al. (1997). However, groundwater is still satisfactory for irrigation purposes (fieldwork in the study area found the average salinity of irrigation water (ECw) to be 8.4 mmhos/cm, see Chapter 5).
5. Due to shortages of water, the Saudi Arabian government has exploited alternative sources such as desalination and now is the world leader in the production of desalinated water for domestic consumption. The combined capacities of the 28 desalination plants in the country are as much as 2.5 million m^3/day.
6. The Saudi Arabian government has also constructed more than 190 dams by 1999 with a combined storage capacity of approximately 475 million m^3.

The role that climate change may play in affecting the existing situation or in efforts to achieve a sustainable water balance in the future is the subject of Chapters 5-7. Therefore, in this context, the following chapter will present observations and estimates of water use in irrigation in the study area in more detail.

Chapter Five: Comparison of Water Use on Farms in Gassim

5.1 Introduction and Aims

Demographers have projected an increase in the Saudi population from 22,7 million inhabitants by the year 2004 to more than 80 million by 2050 (Saudi Press Agency, 2004; Alwatan, 2001). Such a large growth rate is likely to put severe stress on water resources, the environment in general, and on the ability of the agricultural sector to provide sufficient food. Many experts have predicted that, in the future, investments in irrigation and water resource management will become increasingly important. Much of this investment will come in the form of improved water management and productivity (Hargreaves, 1998). Using water economically and efficiently is a problem that confronts farmers and agricultural scientists in all irrigated areas of the world's arid and semi-arid regions. Understanding of the most efficient use of agricultural irrigation water is essential in order to maximise yields economically, and to conserve water (Brown, 1999). Therefore, studying CWR is important in order to achieve various benefits such as conserving water resources, increasing water productivity, and minimizing the costs of production.

This chapter introduces an empirical study of water use in two types of farms (the TFs and CFs) in the area of Gassim. In order to examine the sensitivity of water use to climate change, the chapter presents estimates of ET_O, CWR, IE and IS, based on the current climate. These estimates are recalculated in Chapter 7, given climate change scenarios based on GCMs.

The two types of farm are; modern sprinkler irrigation (CF) and traditional open furrow irrigation (TF). The objective is to identify the main stages of water use on the case study farms and to evaluate and compare their performance in terms of crop productivity and water use efficiency. Standard approaches, following FAO guidelines, are used to achieve this objective. A secondary objective is to collect enough information on water use and climate data to allow for a climate sensitivity analysis of irrigation water use and climate change using climate scenarios for Gassim.

The chapter follows a sequential analysis, firstly with a description of the field work methods, through to a comparison of calculated water use on the farms in Gassim. Figure 5.1 shows an outline of the main steps followed in this chapter to calculate the variables for the analysis. The first part concerns the methods and the choice of the study site. This is followed by sections on soil and water quality and the calculation of ET_O (reference crop evapotranspiration). The final part of the chapter presents the various components of irrigation water use on the two types of farm. This is followed by the overall discussion and conclusions.

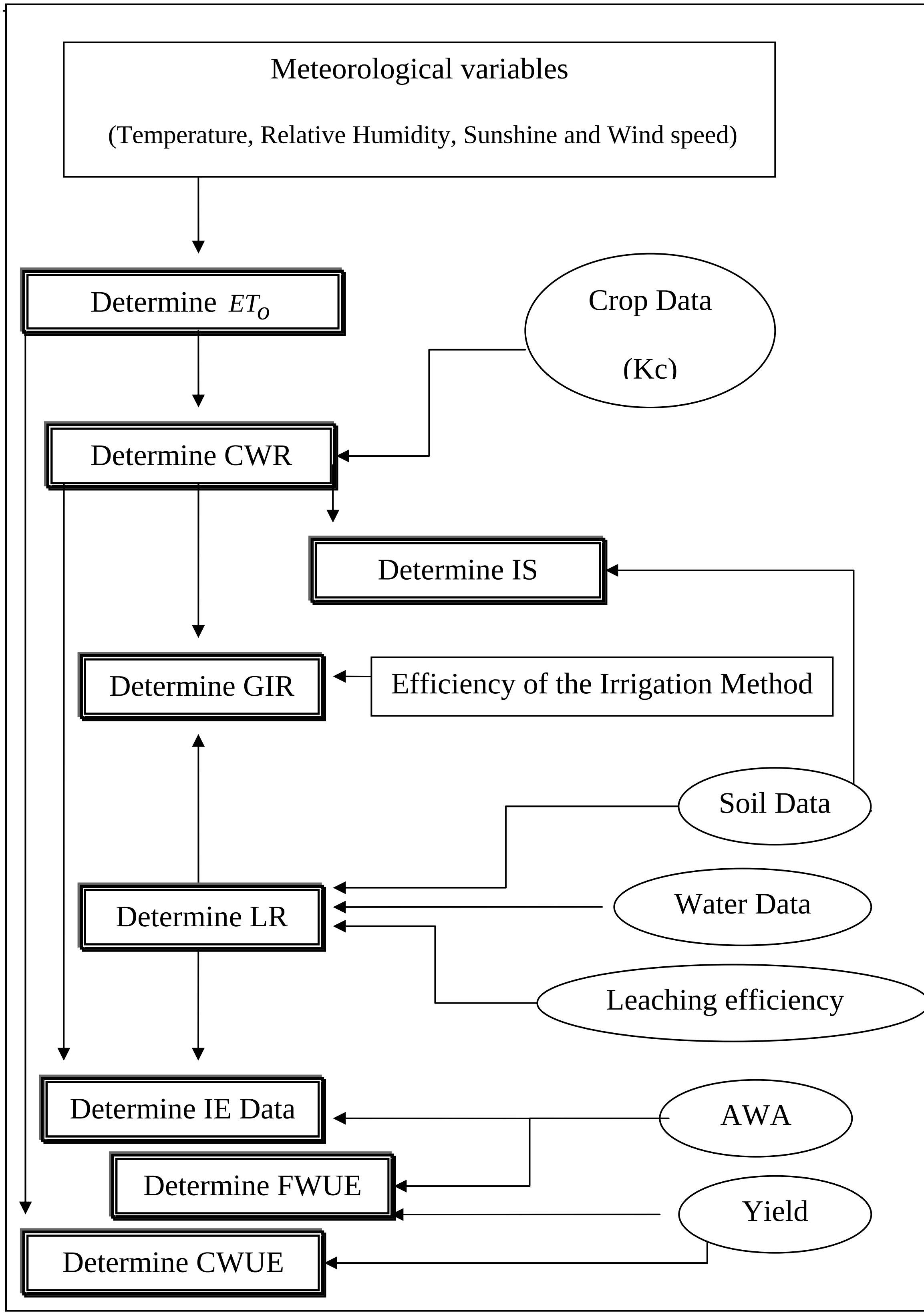


Figure 5.1: Outline of the processes used to calculate ET_o, CWR, LR, GIR, IE, CWUE, and FWUE. All acronyms listed on page vi.

5.2 Field Work

The researcher carried out field studies in Gassim during winter 2003. The choice of Gassim was made to achieve the following objectives:

1. To select two CFs and six TFs in the study area in order to make a comparison between the two types of irrigation systems in terms of water use and water management.
2. Use observations from Unizah weather station to calculate ET_O.
3. To meet with farmers in order to obtain qualitative information about the wheat crop, the irrigation systems used, and the context of water use on their farms.
4. To measure the AWA per irrigation period in each farm, in terms of sprinkler irrigation using flow meters, and surface irrigation using calibrated v-shape weirs (see Chapter 3).
5. To obtain samples of water and soil from each farm for the purpose of calculating LR, IE, GIR and IS.

5.3 Study Farms and Measuring Irrigation Water Use

Agriculture in the study area requires irrigation in all seasons due to the low annual rainfall (less than 100 mm/year). Periods of water deficit occur during the wheat growing season almost every year. Therefore, the wheat crops require additional irrigation from groundwater sources, and in the study area farmers use many sorts of irrigation methods including:

a) Flood,

b) Micro-drip,

c) Micro-spray,

d) Multiple sprinklers,

e) Sprinkler, large guns,

f) Sub irrigation etc.

The irrigation methods used for wheat in the study farms were flooding in the TFs and sprinkler pivots in the CFs.

Eight farms were selected to achieve the research aims. Table 5.1 displays general information about the farms. The figures, collected by the researcher, indicate that the total wheat area of the TFs ranges from 0.5 to 2.7 ha using the surface flood irrigation method, whereas the CFs range from 12 to 2850 ha, using centre pivots. In terms of production yields, the results for the CFs are reasonably accurate as these farms record them carefully, but for the TFs yields were estimated from the number of sacks as weighed by each farmer. The TFs range between 1 and 4.2 tons per farm, while the CFs range between 50 and 17955 tons per farm, which reflects the huge differences in size between the two types of farms, particularly Farm 8. All eight farms use the Yecora Rojo type of wheat, and its planting dates vary from 15th November to 15th January, and the farms generally follow the MAW guidelines.

The aim of the field work was to collect sufficient data to measure the actual water use for the wheat crop in the eight farms. For the six TFs the V-Shape weir technique was utilized (Picture 5.1). This was designed at the Agricultural Research Centre and the Department of Soil Science at Gassim University (see Section 3.5). For the two CFs, flow meters were used to measure the volume of water applied during the irrigation periods on the farms. The water applied in the TFs during typical irrigation applications was measured between three and four times per farm, and then the average amount was calculated for each farm's application. The measurements for the CFs were taken from the farm's records.

Comparative studies of the two types of farm were conducted in order to investigate the relationship between AWA and productivity and CWR (estimated by the Penman-Monteith (PM) method (Allen et al., 1998)).

Materials	**Farm**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Type of farm	Traditional						Commercial	
Total area (ha)	5	11	8	16	50	16	40	40000
Cultivated area (ha.)	3.5	10	6	10	15	12	20	6000
Wheat area (ha)	1	1	0.5	2.7	1.5	1	12	2850
Production (ton)	1.7	1.8	1	4.2	2.5	1.7	50	17955
Type of wheat	Yecora Rojo							
Planting data	Nov 15	Dec 15	Dec 15	Jan 15	Dec 15	Dec 15	Dec 15	Dec 1
Method of irrig.	Surface flood						Sprinkler pivot	

Table 5.1: Information about the farms that were chosen for the field work in Gassim during winter 2003.

Picture 5.1: V- shape weir for measuring irrigation.

5.4 Comparison of AWA between Irrigation Methods

The main difference between the six TFs, which represent the majority of farms in the study area, and the two CFs (much larger in size) was the method of irrigation. (Pictures 5.2 and 5.3). The results of the field work measurements for AWA are listed in Table 5.2. In the TFs AWA ranges between 12663 and 18874 m^3/he/season, whereas in the CFs it was between 7100 and 9341 m^3/ha/season. It should be noted that the figure for AWA in Farm 8 represents the average of eight sprinkler pivots.

Al Al-Shaikh (1993) measured the AWA for wheat with surface flood on farms to the south of Riyadh in Saudi Arabia, and found it to be between 3270 and 11437m^3/ha/season. However, she also found that under the centre pivot it ranged between 2012 and 5417 m^3/ha/season. It is noted that the current study results for AWA are much higher than the Al Al-Shaikh's results, however Al Al-Shaikh does not mention how she measured AWA. Additionally, Al-Taher et al. (1992) measured the AWA of wheat in 32 farms in the Ad Dawadimi area (located to the south of Gassim) and found values for AWA ranging between 4620 and 13965 m^3/ha/season.

The reason why the AWA was much higher in the TFs is that the surface flood method used much larger amounts of water. Most farmers on the TFs usually try to irrigate the wheat crop as abundantly as they can, aiming to achieve higher yields, and most of them have limited awareness about the use of estimating CWR for improved irrigation water scheduling for wheat. Knowledge of crop evapotranspiration is extremely important for optimizing the use of available water for irrigation. The productivity of wheat in the eight farms reveals that in the CFs it is much higher (4.2 and 6.3 ton/ha) than in the TFs (1.6 and 2 ton/ha). The average productivity of wheat in Saudi Arabia is approximately 3.5 ton/ha (Tamimi, 1988).

The AWA values in the TFs represent the direct measurements of the researcher during field work. The exact number and duration of the irrigation periods during the crop season were estimated from conversations with the farmers during the interviews, and this is subject to some uncertainty as the farmers were depending on their memory. Therefore, there may be some random errors embedded in the results of the AWA values, and the large differences in AWA between the farms in the current study, or between these results and the results of other studies, reflect the possibility that some errors may have occurred during the measurement and estimation procedure. For example, in Farm 1 the length of one irrigation in order to fill the field was 12 minutes according to the farmer's estimation (memory), while according to researcher's measurement it was only nine minutes. Three minutes difference generates a discrepancy of about 4967 m^3/ha/season, which is large relative to the overall amount.

To present in a broad approach the uncertainty in the estimates of AWA Table 5.2 also shows upper and lower estimates calculated by assuming a ±20% error in the estimate of water applied. The error ranges between ±2533 mm in Farm 5 to ±3775 mm in Farm 1, which also affects the value of IE in Section 5.12.

<table>
<tr><th colspan="2" rowspan="2">Materials</th><th colspan="8">Farm</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th></tr>
<tr><td colspan="2">Type of farm</td><td colspan="6">Traditional</td><td colspan="2">commercial</td></tr>
<tr><td rowspan="3">AWA for wheat m^3/ha/season</td><td>-20%</td><td>15100</td><td>14108</td><td>10159</td><td>10353</td><td>10131</td><td>13323</td><td rowspan="3">7100</td><td rowspan="3">9341</td></tr>
<tr><td></td><td>18874</td><td>17635</td><td>12699</td><td>12942</td><td>12663</td><td>16654</td></tr>
<tr><td>+20%</td><td>22649</td><td>21162</td><td>15239</td><td>15530</td><td>15196</td><td>19985</td></tr>
<tr><td colspan="2">Productivity (ton/ha)</td><td>1.7</td><td>1.8</td><td>2.0</td><td>1.6</td><td>1.7</td><td>1.7</td><td>4.2</td><td>6.3</td></tr>
</table>

Table 5.2: Results of measurement of AWA during irrigation applications, and the productivity of the eight farms in the Gassim area. Figures in italics represent upper and lower estimates to highlight the range of uncertainty that may be present in the results.

Figure 5.2 shows the relationship between AWA and wheat yield in the eight farms in the study area. The method of irrigation in the CFs uses less water and produces higher yields than in the TFs. Moreover, the higher water use does not increase wheat yield in the TFs (Spearman Rank Correlation Coefficient between the eight farms, r = -.66, while between the six TFs r = -.21). For example, the TFs 1, 2 and 6 use more water than TFs 3, 4 and 5 to achieve almost the same yield. This can be explained by the different agricultural behaviour of the farmers, but some uncertainty may be related to the accuracy of the responses from the farmers during their interviews. In addition, the CFs use several other strategies in cultivating wheat, such as disease control, use of high quality fertilizer, scientific irrigation scheduling, and high quality seed.

Picture 5.2: Methods of surface flood irrigation in one TF.

Picture 5.3: Methods of sprinkler pivot irrigation in one CF.

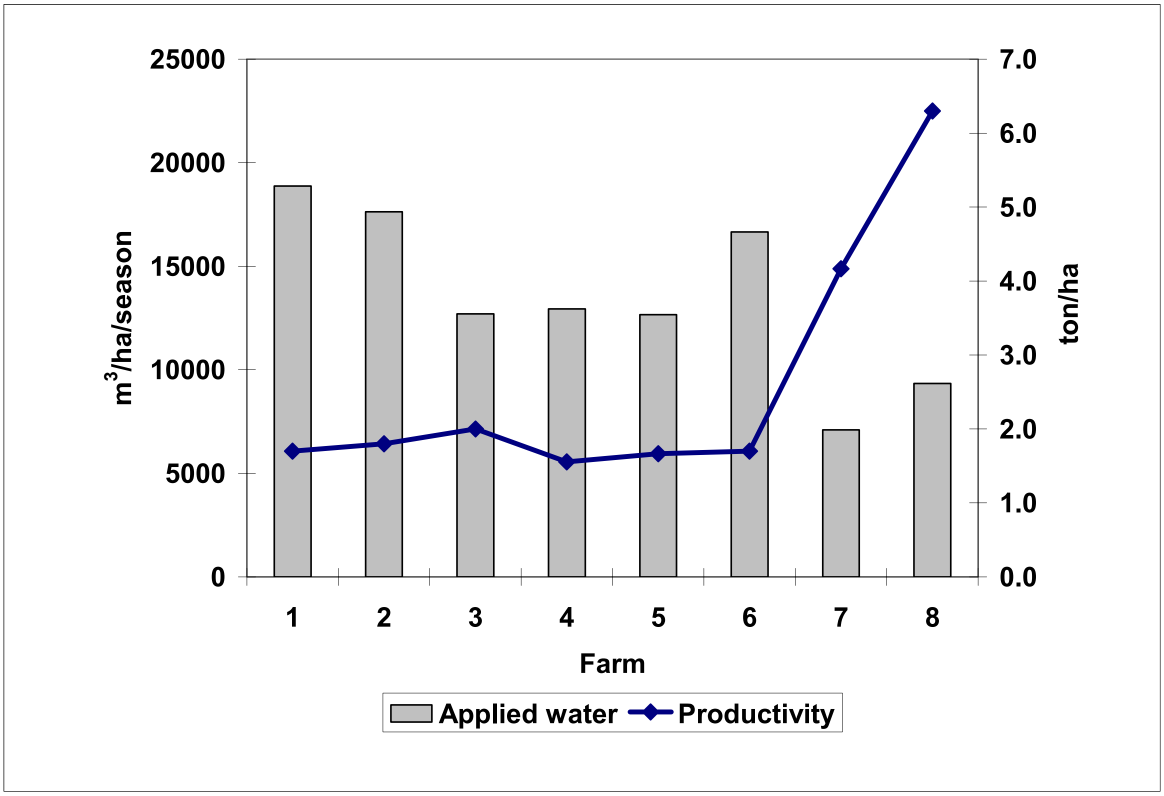


Figure 5.2: The AWA per season for wheat (m^3/ha/season), and productivity (ton/ha) on the eight farms in Gassim.

5.5 Soil Characteristics

It is important to analyse the soil characteristics on the farms in order to assess their influence on the water balance. Therefore, soil samples were taken from the wheat crop fields by digging soil pits on each farm; it should be noted that the soil samples in Farm 8 come from an average of eight different sprinkler pivot areas, while the rest of the farms needed only one sample as the TFs are small and their individual soil surfaces do not vary very much. Additionally, my discussion with the farmers suggested that they do not take into consideration any variation in soil characteristics.

The soil samples were taken at four levels (0-25, 25-50, 50-75, 75-100 cm) and sent to a laboratory for determination of soil texture[1] (soil mechanical analysis), field capacity[2], wilting point[3], bulk density[4] and electrical conductivity in saturation extract (ECe)[5] according to Black, (1965).

Soil characteristics are very important when studying ET_O, CWR and irrigation water use. For example Niyazi (1996) notes that soil texture affects the evaporation rate from the soil surface and the rate and quantity of water uptake by plants. Table 5.3 shows the results of the soil analysis by the Agricultural Research Centre and the Department of Soil Science at Gassim University. Soil characteristics were specified for each farm and were obtained by mechanical analysis. Soil textures in the top soil of these farms are mainly sandy and loamy sand types. The results indicate that ECe ranges between 4.7 and 12.2 mmhos/cm. Wheat crop tolerance to salinity of ECe, with minimum effects on crop yield, is from 6 to 20 for max ECe (Al-Amoud, 1999). Therefore, the ECe values obtained here suggest that it is appropriate to plant wheat in the study area without problems from soil salinity, as the wheat salt tolerance level for average production potential is 6.7 mmhos/cm (MAW, 1988). The above computations are used to estimate the LR (see Section 5.9).

[1] Soil texture: The relative proportions of sand, silt and clay in a soil (Gerrard, 2000).
[2] Field capacity: The situation where the forces holding water to soil particles are equal to the downward forces of gravitational pull; the water content of a soil after drainage under gravity has been completed (Gerrard 2000).
[3] Wilting point: The lower limit of soil water availability (Perrier et al.,1991).
[4] Bulk density: The weight of soil per unit volume; can be wet bulk density, which includes water content, but is usually expressed on an oven-dry basis (Gerrard, 2000).
[5] Electrical conductivity (EC): Conductivity of electricity through water (ECw) or an extract of soil (ECe) (SSSA, 2001).

Farm No	Sample No	Depth Cm	Wilting point % weight	Field Capacity % weight	Sand %	Silt %	Clay %	Texture	ECe (mmhos/cm)	Aver. ECe
1	S1	0-25	6.6	13.1	74	6	20	Loamy Sand	5.8	5.70
	S2	25-50	5.3	9.6	88	2	10		4.7	
	S3	50-75	2.9	6.4	94	0	6	Sand	6.3	
	S4	75-100	1.1	3.3	94	0	6	Sand	6	
2	S1	0-25	4.2	10.3	84	7	9	Loamy Sand	5.8	6.00
	S2	25-50	4.6	11	85	5	10		6.2	
	S3	50-75	4	10.1	81	17	2		5.9	
	S4	75-100	4.5	12.2	82	13	5		6.1	
3	S1	0-25	4.8	11.2	84	6	10	Loamy Sand	6.2	6.63
	S2	25-50	4.3	10.1	80	12	8		6.5	
	S3	50-75	4.7	10.1	80	8	12		7.1	
	S4	75-100	4.6	9.6	80	14	6		6.7	
4	S1	0-25	5.1	14.4	82	12	6	Loamy Sand	4.5	5.23
	S2	25-50	6.1	17.3	76	14	10		5.5	
	S3	50-75	8.9	13.6	84	14	2		5.3	
	S4	75-100	6.3	13.9	88	10	2		5.6	
5	S1	0-25	4.7	8.9	80	14	6	Loamy Sand	5.1	5.45
	S2	25-50	6.4	13.7	74	16	10		5.6	
	S3	50-75	7.8	15.3	80	14	6		5.5	
	S4	75-100	8.5	19.8	74	16	10		5.6	
6	S1	0-25	5.9	12.1	84	10	6	Loamy Sand	5.7	7.15
	S2	25-50	9.5	25.6	78	14	8		6.7	
	S3	50-75	8.7	16.1	74	22	4		6.6	
	S4	75-100	8.9	16.5	66	26	8		9.6	
7	S1	0-25	6.7	13.2	82	8	10	Loamy Sand	12.2	10.78
	S2	25-50	6	11.8	80	6	14		13	
	S3	50-75	7.2	13.7	76	12	12		10.7	
	S4	75-100	8.5	19.8	70	22	8		7.2	
8	S1	0-25	5.5	13.4	80	11	9	Loamy Sand	10.1	9.65
	S2	25-50	4.1	9.9	79	10	11		11	
	S3	50-75	3	9.5	77	13	10		9.2	
	S4	75-100	2.9	10	75	16	9		8.3	

Table 5.3: Physical properties and mechanical analysis of soil samples for the eight study farms.

5.6 Water Quality Analysis

Irrigation water samples were obtained from the local wells which serve as the source of water for all the farms. Water characteristics are also crucial for the calculation of the components of irrigation water use, especially the LR (Section 5.11). Consequently, water samples were taken directly from the pumps (Picture 5.4) and taken to a laboratory for determination of the electrical conductivity of the irrigation water (ECw mmhos/cm).

Table 5.4 shows the results of the chemical analysis of the samples analysed by the Agricultural Research Centre and the Department of Soil Science at Gassim University. Salinity of irrigation water (ECw), expressed in mmhos/cm, ranges from 0.7 to 14.0 with an average of 8.4. These values indicate that the ECw is very high in most of the TFs, and therefore the irrigation water requires leaching (Figure 5.3). This means that the water quality is classified as saline, except for the water in Farms 7 and 8 as they draw from different aquifers. It should be noted that the wheat crop's tolerance to salinity (ECw) with average production potential is 4.5 mmhos/cm (MAW, 1988).

Materials	**Farm**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Type of farm	traditional						commercial	
ECw mmhos/cm	7.8	8.3	14	9.7	12	12.1	2.5	0.71

Table 5.4: Descriptive statistics of irrigation water quality (groundwater) in Gassim.

Picture 5.4: Water samples were obtained from the pumps of the eight farms and taken to a laboratory for analysis.

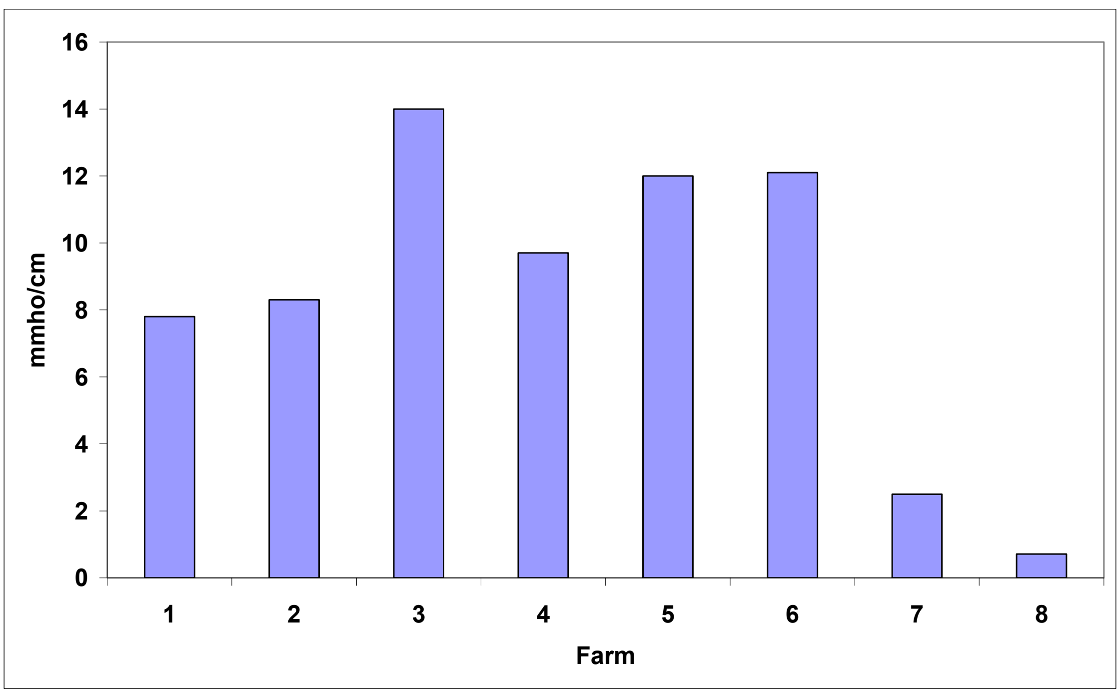


Figure 5.3: The ECw of irrigation water in each of the eight farms.

5.7 Determination of Potential Evapotranspiration (ET_o)

> *"Evaporation is the process whereby liquid water is converted to water vapour (vaporization) and removed from the evaporating surface (vapour removal). Water evaporates from a variety of surfaces, such as lakes, rivers, pavements, soils and wet vegetation"* (Allen et al., 1998, p1).

Furthermore, ET_o is the combined process of evaporation from the Earth's surface and transpiration from vegetation (Allen et al., 1998). ET_o is reference crop evapotranspiration in mm per time step and it is defined in Section 2.3.4. ET_o is of considerable importance for calculating CWR due to its relevance to irrigation scheduling. Therefore, one objective of this study is to determine the ET_o for Gassim using the PM method (see Equation [3.2]) A FORTRAN program was written to calculate ET_o values on a monthly basis using the meteorological data from Gassim for 25 years (1976 to 2000). The program results were validated by comparison with calculations performed manually and with results from the CROPWAT program written by FAO (Version 4.2. 1998, website - http://www.fao.org/landandwater/aglw/cropwat.stm).

In Saudi Arabia many researchers have used the Penman method or PM method (MAW, 1988; Basahi, 2002) and found them to be the best equations for estimating the ET_o for an arid area. Table 5.5 shows the average monthly climate observations and ET_o for Gassim (obtained by multiplying the number of days per month by the daily ET_o). Peak ET_o typically occurs during the summer (7.9 mm/day in June and July). In contrast, the lowest ET_o occurs in December (2.3 mm/day). The average monthly ET_o value is 5.2 mm/day. Figure 5.4 shows the monthly average total ET_o and Figure 5.5 shows the overall monthly average

values of the climatic elements that were used to calculate ET_O, and the average values over the 25 years (1976-2000).

Month	Temp. °C	RH %	Wind m/s	Sunshine hour	ET_O mm/mon.	ET_O mm/day
1	12.5	53.6	1.9	6.0	74.8	2.4
2	14.7	44.0	2.2	6.6	96.1	3.4
3	18.7	38.5	2.5	6.6	144.5	4.7
4	24.5	32.5	2.5	7.0	181.3	6.0
5	30.3	21.4	2.4	7.5	228.9	7.4
6	33.4	12.4	2.2	9.0	236.0	7.9
7	34.5	11.7	2.1	9.5	245.4	7.9
8	34.3	11.5	1.9	8.6	217.5	7.0
9	31.8	13.2	1.7	7.9	171.6	5.7
10	26.4	22.5	1.8	7.4	142.6	4.6
11	19.2	40.7	2.0	6.4	94.7	3.2
12	14.3	51.8	1.8	6.1	72.7	2.3
Average	24.5	29.5	2.1	7.4	158.8	5.2

Table 5.5: Average monthly climate and ET_O for 25 years (1976-2000).

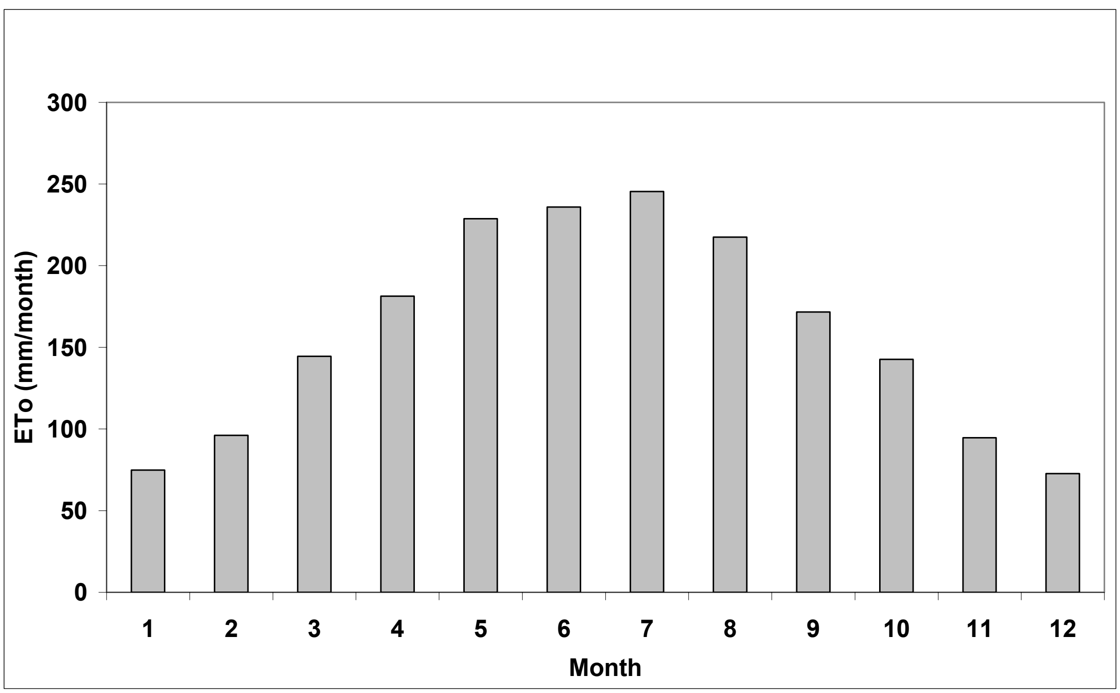


Figure 5.4: Average monthly ET_O in Gassim for the period 1976-2000 (mm/month).

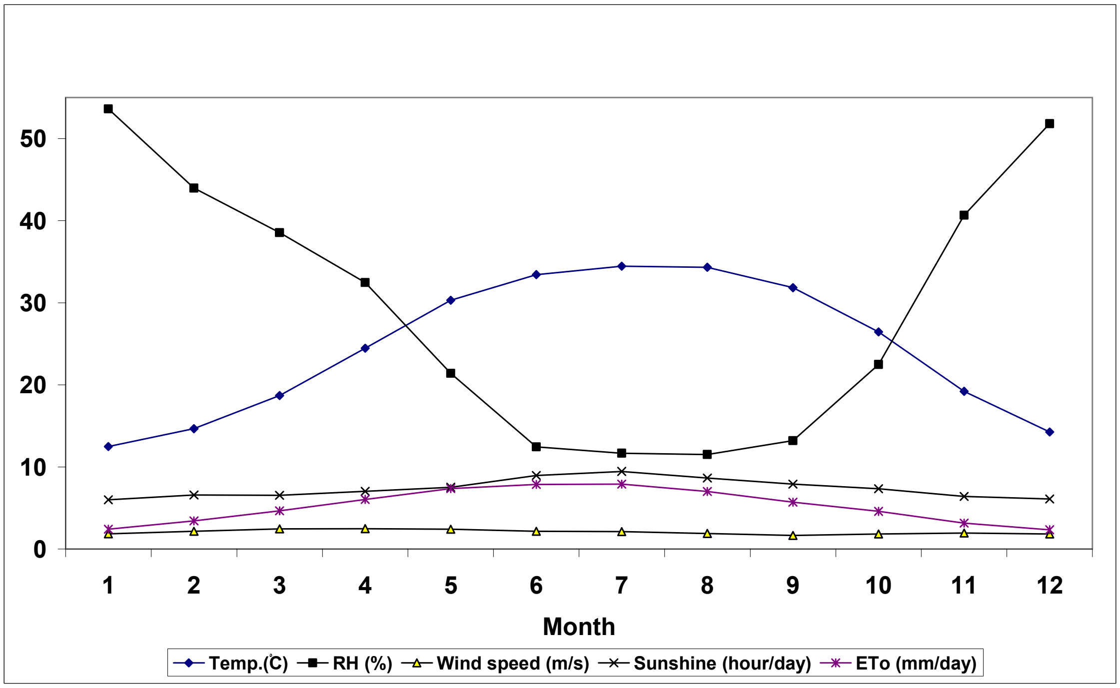


Figure 5.5: Monthly average values of the climatic elements and the ET_O over 25 years (1976-2000) in Gassim.

Table 5.6 shows ET_O at specific times during the growing season for wheat in Gassim. The growing season was determined for each farm during field work, for example, by using the date for planting and for harvesting the wheat crop, which differed from one farm to another, as follows:

- Farm 1: mid-November until 24th March.
- Farm 8: from 1st December until 9th April.
- Farms 2, 3, 5, 6, and 7: mid-December until 23rd April.
- Farm 4: mid-January until 24th May.

The length of the average growing season is 130 days. Table 5.6 shows that the values of ET_O range from 406 mm/season for Farm 1 to 640 mm/season for Farm 4. The differences in total ET_O for each season are significantly influenced by the sowing date. The reason why the farms use different sowing dates is that the

period for wheat planting is relatively long and lies between mid-November and mid-January. This allows other factors to influence the farmers' decision of when to plant; farmers might follow the MAW guidelines, others local guidelines or their experience, and still the availability of sowing machines, especially in the CFs.

Farm No	Month	Temp. °C	R.H. %	Sun. h	Wind. m/s	ET_O -PM mm/day	ET_O -PM mm/period
1	15 Nov	19.2	40.7	6.4	2.0	3.2	50.5
	Dec.	14.3	51.8	6.1	1.8	2.3	72.7
	Jan.	12.5	53.6	6.0	1.9	2.4	74.8
	Feb.	14.7	44.0	6.6	2.2	3.4	96.1
	24 Mar.	18.7	38.5	6.6	2.5	4.7	111.9
	Total						406
8	1 Dec.	14.3	51.8	6.1	1.8	2.3	72.7
	Jan.	12.5	53.6	6.0	1.9	2.4	74.8
	Feb.	14.7	44.0	6.6	2.2	3.4	96.1
	Mar.	18.7	38.5	6.6	2.5	4.7	144.5
	9 Apr.	24.5	32.5	7.0	2.5	6.0	54.4
	Total						442.5
2-3-5-6-7	15 Dec	14.3	51.8	6.1	1.8	2.3	39.9
	Jan.	12.5	53.6	6.0	1.9	2.4	74.8
	Feb.	14.7	44.0	6.6	2.2	3.4	96.1
	Mar.	18.7	38.5	6.6	2.5	4.7	144.5
	23 Apr.	24.5	32.5	7.0	2.5	6.0	139
	Total						494.2
4	15 Jan	12.5	53.6	6.0	1.9	2.4	41
	Feb.	14.7	44.0	6.6	2.2	3.4	96.1
	Mar.	18.7	38.5	6.6	2.5	4.7	144.5
	Apr.	24.5	32.5	7.0	2.5	6.0	181.3
	24 May	30.3	21.4	7.5	2.4	7.4	177.2
	Total						640.1

Table 5.6: The climatic factors and the ET_O during the growing seasons for each farm (1976-2000).

5.8 Determination of CWR

Calculating CWR is important for water resource management, and planning CWR can be defined as:

> *''The depth of water needed to meet the water loss through ET_O of a disease-free crop, growing in a large field under non-restricted soil conditions including soil water and fertility, and achieving full production potential under a given growing environment.''* (Doorenbos and Pruitt, 1977, p.1). Moreover, water requirement may be defined as :
> *''the quantity of water, regardless of its source, required by a crop or diversified pattern of crops in a given period of time for its normal growth under field conditions''* (MAW, 1988, p.1).

This section outlines the calculation of peak CWR rates of wheat for the eight study farms (explained in Section 3.6.2). The CWR of wheat was calculated for the whole season (130 days on average) for each farm.

The monthly CWR for wheat, based on ET_O, was computed by taking into account the crop characteristics (Kc of the wheat crop, which was determined from locally adjusted values, MAW, 1988). Table 5.7 shows the total CWR for each farm in the study area. Sowing date plays a significant role in determining the ET_O and the amount of water which should be supplied to the crop during the different stages of growth; farms with later sowing dates have higher CWR. To illustrate this, the total CWR of Farm 1 is only 3038 m^3/ha/season as the planting date starts in the middle of November, while in Farm 4 it is 5188 m^3/ha/season as the planting date starts on the first of January. Therefore, Farm 1 saves about 2150 m^3/ha/season because the farmer sows approximately 61 days earlier, when the temperature is relatively low and the duration of sunshine is reduced. It is clear that sowing early is one factor in achieving benefits, such as reducing water use and minimizing the cost of production, however, there may be trade-offs with differences in yield due

to the lower temperatures and radiation associated with early planting. Moreover, Figure 5.6 shows that the total CWR (mm/season) for wheat is low during the period of early crop establishment. It then reaches a peak during the final growth phase, and falls again when the crop gains maturity.

Al-Taher et al. (1992) calculated the CWR for wheat in Ad Dawadimi using the Blaney and Criddle method. They found that the CWR of wheat planted on the 1st of December (for a 130 day season) reached 3498 m^3/ha/season. This is quite similar to Farm 8 (3457 m^3/ha/season), which starts planting on the same date. Mustafa et al. (1989) estimated the CWR for wheat in each region of Saudi Arabia, and obtained values ranging between 3780 and 6730 m^3/ha/season. Moreover, Al-Omran et al. (1992) calculated ET_O according to the Jensen-Haise method and then estimated the CWR for wheat in the central and eastern regions of Saudi Arabia, with planting dates in November. They found that the value of CWR for wheat is 5510 m^3/ha/season, which is much higher than Farm 1 in the present study, although the planting date is almost the same. This difference may be due to differences in the methods used to estimate ET_O.

In this study, the local rainfall is ignored, as in the area it is very low, about 92 mm/year. During rainfall events, most of the rainfall is lost through runoff or deep percolation, so it cannot be relied upon to mature the agricultural crops. MAW (1988) and Abderrahman et al. (1993) noted that the average rainfall values in most of the regions of Saudi Arabia are less than 125 mm/year, and that therefore the contribution of rainfall to the irrigation requirements can be ignored as it is too low and irregular. Consequently, 100% of the CWR must be provided from groundwater through irrigation to ensure sufficient moisture for the guaranteed maturation of wheat through the full season.

Materials	**Farm**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Type of farm	traditional						commercial	
Planting data	Nov 15	Dec 15	Dec 15	Jan 15	Dec 15	Dec 15	Dec 15	Dec 1
CWR m^3/ha/sea-son	3038	3931	3931	5188	3931	3931	3931	3457

Table 5.7: CWR of wheat in Gassim, depending upon planting date at each farm.

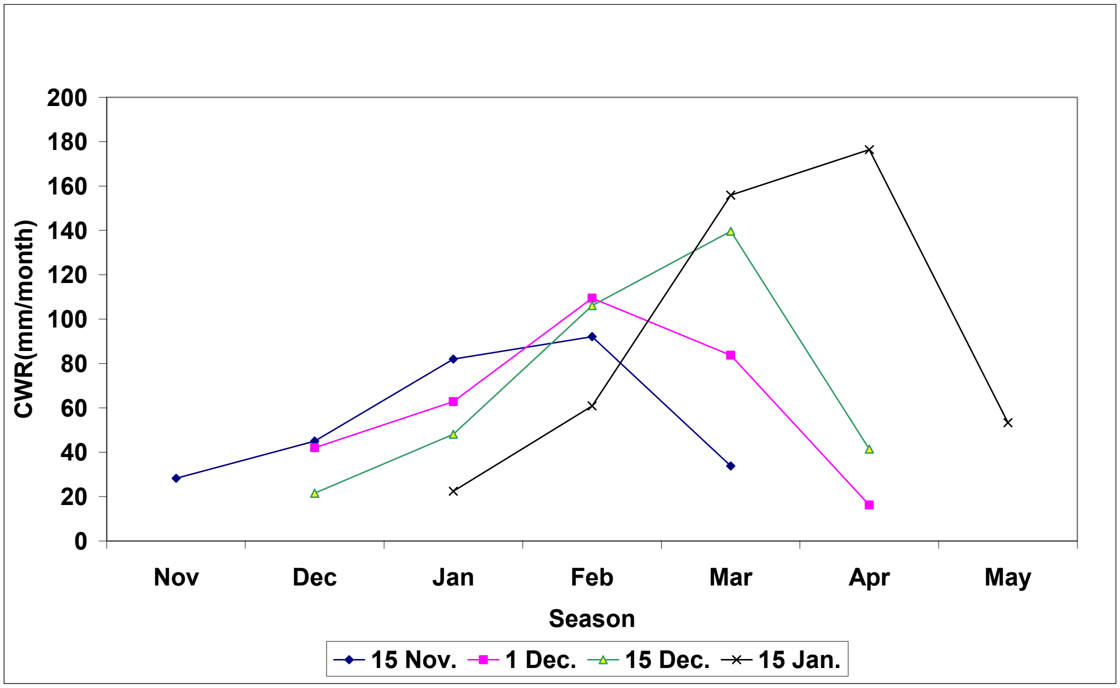


Figure 5.6: The effect of the planting date on CWR for wheat in Gassim (mm/month).

5.9 Determination of Leaching Requirement (LR)

The leaching of salts is required in order to maintain acceptable soil salinity levels. This is achieved by extra applications of water to both dissolve the unwanted salts down to below the root zone, and to wash off the surface salts away from the planted area. Without maintaining an acceptable salt balance in the root zone, it would not be possible to continue to grow crops in many irrigated areas of the world (Kijne, 2003). The total amount of water for leaching depends on the type of crop and the salinity of the water. The LR was calculated for the eight farms using the results of the water analysis (Table 5.4), particularly the values of ECw. Due to quite high ECw concentrations on some farms, LR should be considered in the calculation of total CWR. In Gassim the water table is relatively deep and the soil relatively saline, possibly due to excessive irrigation by some farms (especially the TFs who may be insufficiently acquainted with this issue). They may have been applying excessive quantities of water during irrigation periods. Smajstrla et al. (1995) mentioned that generally CWR should not include water applied for the leaching of salts; but it is the case that water is required for this purpose for crop production. Total CWR should therefore be determined by adding water needed for LR to the irrigation requirement calculated from equation [3.9]. This was done for all eight farms and the results are listed in Table 5.8.

The value of the coefficient for the LR ranges between 0.02 (Farm 8) and 0.39 (Farm 3). This means that Farm 8 needs only 68 m^3/ha/season during the season to add to the CWR, which represents just 2% of the total CWR, in order to maintain acceptable levels of soil salinity. On the other hand, Farm 3 needs 1529 m^3/ha/season, which represents 39% of CWR. This is because of differences in the quality of the water used for irrigating wheat; ECw was 14 mmhos/cm on Farm 3 and only 0.71 mmhos/cm on Farm 8. Comparing these Figures with Al-Taher et al. (1992), he calculated the LR of wheat in 32 farms in Ad Dawadimi area, and found that the values ranged between 213 to 2340 m^3/ha/season (the water in Ad Dawadimi is more saline than in Gassim). For this study, the values of water

required for the LR are added to the CWR in order to allow for sustainable (in terms of soil salinity) yields of wheat.

However, during the field work the researcher found that all the TFs irrigated their wheat crops regardless of the salt concentration of the water. They generally used large amounts of water for irrigation (see Section 5.4), usually exceeding the needs for the crop growth and the LR. The role of such management factors is discussed in Section 5.4 (discussion, and in relation to climate change in Chapter 7).

Materials	**Farm**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Type of farm	traditional						commercial	
CWR m^3/ha/season	3038	3931	3931	5188	3931	3931	3931	3457
LR m^3/ha/season	658	906	1529	1398	1310	1321	273	68

Table 5.8: Calculation of Leaching Requirement (LR) for the eight farms in the study area.

5.10 Estimation of Gross Irrigation Requirement (GIR)

The GIR is defined as the volume of water (m^3/hectare/season) required for meeting the net CWR, including the LR (MAW, 1988). The gross amount of water delivered from the supply must be greater than the net CWR by a factor which depends on the efficiency of the irrigation method (eff), which is assumed to be 55% for surface methods and 70% for sprinkler methods according to average measurements from the MAW (MAW, 1988). Abderrahman et al. (2003) reported on local experience of the efficiency of different types of irrigation systems in different regions of Saudi Arabia. They adopted values for average irrigation efficiency of the centre pivot sprinkler irrigation method of 70%. Therefore, the

climate, crop, water and soil data can be combined to determine the GIR, according to equation [3.10].

Table 5.9 shows CWR and LR, as previously discussed, and also shows values of GIR (in m^3/hectare/season) which range between 5039 and 12912 m^3/hectare/season, with an average of 9189 m^3/hectare/season. It is clear from Table 5.9 that farms which use poor quality water in terms of salinity, such as Farms 3, 5, and 6, need much higher volumes of water than other farms, such as 7 and 8. Farm 4 requires the highest amount of water as its planting date is relatively late (15th December). Moreover, Farms 7 and 8 use the sprinkler method for which it is assumed there is greater efficiency in water use.

These GIR results can be compared with other estimates from the MAW (1988). These indicate that the GIR for wheat in the central region of Saudi Arabia under the centre pivot method ranged between 6471 and 7500 m^3/ha/season, for quality water that ranged between 0.78 and 2.34 mmhos/cm, respectively. These values are not dissimilar to the figures from the current study for Farms 7 and 8 which have similar water quality. Under the surface method, the MAW published values for GIR which ranged between 8236 and 13016 m^3/ha/season, for a water quality range between 0.78 and 6.25 mmhos/cm, respectively, which are similar values to Farms 1-6, all of which used the same method.

Materials	**Farm**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Type of farm	traditional						commercial	
CWR m^3/ha/season	3038	3931	3931	5188	3931	3931	3931	3457
LR m^3/ha/season	658	906	1529	1398	1310	1321	273	68
CWR+LR m^3/ha/season	3696	4837	5460	6586	5241	5252	4204	3525
GIR m^3/ha/season	7051	9289	11696	12912	10721	10766	6035	5039

Table 5.9: Gross Irrigation Requirement (GIR).

5.11 Determination of the FWUE and CWUE

Field water use efficiency (FWUE) is defined as the ratio of grain yield to the total amount of water used in the field (I.A.R.I, 1977), and can be expressed in terms of kg/m^3. Values for FWUE were calculated in order to compare the two irrigation methods according to equation [3.5] using AWA and yield. Table 5.10 lists the calculated values of FWUE for each farm, and clearly shows that it is strongly dependent upon the method of irrigation. In Farms 1 to 6, which use the surface flood method, the values of FWUE are very low, 0.09 - 0.16 kg/m^3. This can be compared with the ratio that Perrier et al. (1991) suggested that in order to produce 1 kg of wheat grain under fully irrigated conditions, about 1 to 2 m^3 of irrigation water is required. However, Farms 7 and 8, which use the sprinkler pivot produce 0.59 and 0.67 kg/m^3, respectively, which is significantly higher than, e.g. Farm 1, which produces only 0.09 kg of yield per m^3 of water use. These results can be compared with other Saudi Arabian studies e.g. Kassem et al. (2003), who determined the FWUE of barley under the centre pivot method in the Gassim area. He found values ranging between 0.35 and 1.0 kg/m^3. Moreover, in the Alkarej area, which is located to the south of Riyadh, Al Al-Shaikh (1993) determined the FWUE of wheat under the surface flood method and obtained values between 0.10 and 0.46 kg/m^3, an average of 0.19 kg/m^3. She also studied the centre pivot method, and obtained values between 0.19 to 0.80 kg/m^3, with an average of 0.45 kg/m^3. In this study, the averages for the TFs and the CFs are 0.12 and 0.63 kg/m^3, respectively.

It can be concluded that the method of irrigation offers an explanation for some of these differences, but not for all of them; the CFs use modern methods for cultivation as a business, whereas the TFs are not so concerned with or knowledgeable about these approaches, and this is discussed further in Section 5.4 and in Chapter 7.

Crop water use efficiency (CWUE) is defined as the ratio of crop yield to the amount of water required by the crops in the process of ET_O (I.A.R.I, 1977). Table 5.10 shows the calculated values of CWUE, which range between 0.24 and 0.42 kg/m^3 for the TFs, with an average of 0.35 kg/m^3, whereas in the CFs, the average is 1.13 kg/m^3. This latter average can be compared with a previous study by Kassem et al. (2003), who calculated CWUE values for barley under the centre pivot method resulting in values of 0.48 -1.53 kg/ m^3, similar in magnitude to the current results.

Materials	**Farm**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Type of farm	Traditional						commercial	
FWUE (kg/m^3)	0.09	0.10	0.16	0.12	0.13	0.10	0.59	0.67
CWUE (kg/m^3)	0.42	0.36	0.40	0.24	0.34	0.34	0.84	1.42

Table 5.10: Field water use efficiency (FWUE) and crop water use efficiency (CWUE) for each farm.

5.12 Determination of Irrigation Efficiency (IE)

The expression 'irrigation efficiency' is defined as the percentage ratio of ET_O to the amount of water applied (Perrier et al., 1991). Table 5.11 shows that the values of IE calculated according to equation [3.7], range from 19.6% at Farm 1 to 59.2% at Farm 7, with an average of 38.8%. The values of IE in the fields studied are generally very low and similar to other studies such as Al-Taher et al. (1992) in Ad Dawadimi, where it was found that the values of IE for wheat irrigated under the centre pivot method range from 27% to 78%. Another study by Al-Taher (1994), in Yabrin Oasis, which is located in the south of Saudi Arabia, found that

the values of IE for alfalfa range from 19% to 70%. Moreover, Al Al-Shaikh (1993) reported that the IE for wheat, irrigated under the surface method in the Alkarag area, ranges between 16% and 50% with an average of 24%. However, under the centre pivot method he found values ranging between 31% and 78%, with an average of 53%. On a global scale, Ragab et al. (2002) determined that the overall global average of agricultural water use efficiency is 40%, meaning that more than half of the water allocated and supplied for irrigation is not used directly for biomas production.

The low IE values for the TFs are due to the method of irrigation, poor management practices (unskilled labour, no incentives), and to ineffective irrigation design and layout. Some of these inefficiencies could be minimized through improved irrigation design and implementation, and by improved management practices. Two reasons could explain why the IE in Farm 8 is lower than in Farms 3 to 5: firstly Farms 3 to 5 have high LR values (153, 140 and 131 mm, respectively), whereas Farm 8 has only 7 mm which means if the LR is dropped, then the IE for Farms 3 to 5 would be 31%, 40% and 31%, respectively. Secondly, IE in Farm 4 is higher than in Farm 8 because Farm 4 has higher water demands as the planting date is later, on the 15th January.

IE was again calculated by assuming uncertainty levels of ±20% in the estimation of AWA (see Section 5.4 and Table 5.2). By assuming -20% in AWA, the IE ranges between 24.5% in Farm 1 and 63.6% in Farm 4. On the other hand, +20% in AWA changes the IE to range between 16.3% in Farm 1 and 42.4% in Farm 6 (Table 6.11). There are differences between the two types of farms but given the uncertainty in the results, the differences in IE are not very significant.

There are debates about the calculation, meaning and validity of traditional IE definitions. For example, Seckler et al. (2003) stress the idea of recharge from irrigation water that is not used by the crop, so that water can be reused and is not a true loss. Seckler et al. (2003, p. 38) indicated that;

> *''One of the cardinal features of water use is that, when water is used, not all of it is 'used up'. Most of the water remains in the hydrological system, where it is available for reuse or recycling. As water is recycled through the hydrological system, the efficiency of use increases''.*

However, the method used in this study to estimate IE is the more commonly used classical concept of efficiency, which ignores recycling and thus may tend to underestimate efficiency. Seckler et al. (2003) argue the traditional approach has led to mistakes in thinking about irrigation policy and management. Newer 'neoclassical' concepts represent attempts to integrate water recycling into the concept of water-use efficiency by assuming only some of the excess water is truly lost from the hydrological system. Most of it is captured and recycled somewhere else in the system. Seckler et al. (2003) give an example from the Nile irrigation system in Egypt to show that the average classical IE is about 50% but a series of estimations of the 'neoclassical' IE in the system as a whole has resulted in an estimate of 87%. They also conclude that 'neoclassical' concepts have not been widely accepted in the general community of irrigation and water resource practitioners. In the example of Gassim it is quite likely that some proportion of the excess irrigation water will recharge groundwater. However, this may contribute to higher salinity levels as water is recycled.

Figure 5.7 compares the measured AWA in the eight farms with the estimated values of CWR (including LR). There are significant differences between the values, particularly for the TFs, and this reflects the amount of water lost through poor irrigation practice. Perhaps the primary reason for these large differences between the TFs (Farms 1 to 6) in terms of AWA, and particularly between Farms 1, 2, and 6 against Farms 3, 4, and 5, is on account of the differences in the management practice of these farms.

Materials	**Farm**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Type of farm	Traditional						commercial	
IE % (AWA -20%)	*24.5*	*34.3*	*53.7*	*63.6*	*51.7*	*39.4*		
IE %	**19.6**	**27.4**	**43.0**	**50.9**	**41.4**	**31.5**	**59.2**	**37.7**
IE % (AWA +20%)	*16.3*	*22.9*	*35.8*	*42.4*	*34.5*	*26.3*		

Table 5.11: IE for each farm. Figure in italics represent upper and lower estimates to highlight the range of uncertainty that may be present in the results.

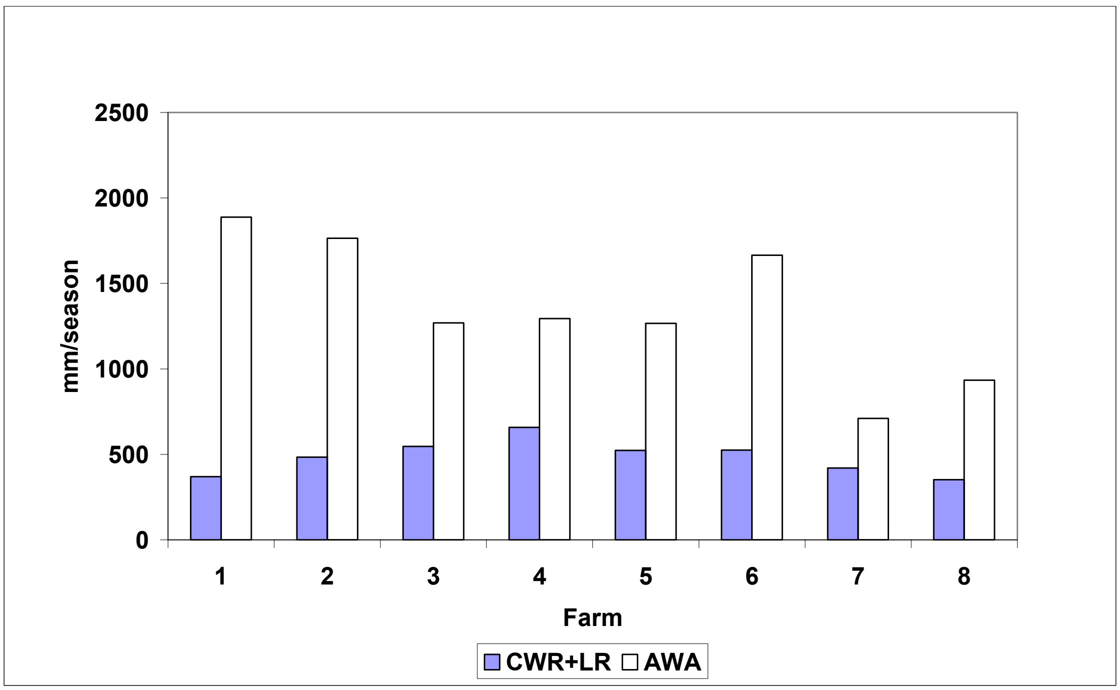


Figure 5.7: Comparison between CWR+LR and AWA in the eight farms.

5.13 Determination of Irrigation Scheduling (IS)

The IS for wheat, or for any crop, defines the depth of irrigation application (in mm), and the interval between irrigation applications (in days) during the entire growth stage (Abderrahman et al., 2003), or in other words, the IS for wheat is the volume of irrigation water that ideally should be applied to the wheat, and how often this is done. Optimum scheduling of irrigation is by far the most important means for improving crop water productivity (Oweis et al., 2003). Information on when and how much to irrigate is needed in order to reduce any unwanted effects of water stress on production (Zhang, 2003).

The depth of irrigation application (in mm) and the interval between irrigation applications were calculated through the CROPWAT model FAO, (see Section 3.7.3). In order to calculate IS, different methods of irrigation scheduling had to be considered, and in this study the water budget approach was used. This depends on ET_o, CWR, effective rainfall, and soil and crop characteristics. The contribution of rainfall to the irrigation requirements was ignored (see Section 5.8).

In the study area, and especially in the TFs, many farmers apply more water than is needed to fill the soil profile to field capacity. In order to compare the ideal IS, as calculated by the CROPWAT model (type one), with the reality or actual IS (type two) Tables 5.12 a-d list, as examples, Farm 6 (a TF) and Farm 7 (a CF). These show the interval in days between irrigation applications, and the irrigation depth applied (in mm) for both types. In terms of type one, the results differ from Farm 6 to Farm 7 depending on the type of soil (or the available moisture). In Farm 6, the depth of irrigation application and the interval between irrigation applications differs from one stage to another, according to the varying growth stages.

In general, irrigation starts on the first planting date for wheat but the amount differs between the two farms. The intervals between the respective irrigation

applications during the rest of the season range from 9 to 27 days, and the depths of those irrigation applications in the two farms range between 12.6 and 78.3 mm. This is the idealised approach, but of course the realty is different to the FAO optimized applications, and the actual applications are listed in Table 5.12 b. These show regular irrigation intervals in Farm 6 at eight days with 111 mm of water applied each time, giving a total of AWA of 1665 mm/season (higher than CWR by about three times). Farm 7 uses sprinkler pivots and the actual IS is listed in Table 5.12 d, showing that irrigation intervals are every day for 10 days and then every 3 days for the rest of season applying 15.7 mm each time with a total AWA of 710 mm. Improving the IS, or the delivery of water, is one adaptation in water management which is discussed in Chapter 7.

a- Farm 6		
Date	**Irrigation intervals (days)**	**Irrigation depth applied (mm)**
15-Dec	0	15.3
11-Jan	27	36.8
02-Feb	22	55.1
18-Feb	16	58.7
03-Mar	13	56.1
15-Mar	12	59.4
26-Mar	11	60.9
12-Apr	17	78.3

b- Farm 6		
Date	**Irrigation intervals (days)**	**Irrigation depth applied (mm)**
15-Dec	8	111
22-Dec	8	111
30-Dec	8	111
07-Jan	8	111
15-Jan	8	111
23-Jan	8	111
31-Jan	8	111
08-Feb	8	111
16-Feb	8	111
24-Feb	8	111
04-Mar	8	111
12-Mar	8	111
20-Mar	8	111
28-Mar	8	111
05-Apr	8	111

c- Farm 7		
Date	**Irrigation intervals (days)**	**Irrigation depth applied (mm)**
15-Dec	0	12.6
03-Jan	19	24.7
23-Jan	20	37.6
07-Feb	15	46.8
19-Feb	12	45.5
02-Mar	11	47.4
12-Mar	10	48.5
21-Mar	9	48.2
31-Mar	10	54.7
17-Apr	17	67.8

d- Farm 7		
Date	**Irrigation intervals (days)**	**Irrigation depth applied (mm)**
15-24 Dec	1 (10 times)	15.7
1 Jan - The end of season	3 (35 times)	15.7

Table 5.12 a-d: Irrigation scheduling for a wheat crop planted as a single block on 15th December (Farms 6 and 7) in the Gassim area (a and c calculated using FAO CROPWAT, b and d according to actual irrigation).

5.14 Discussion and Conclusions

This chapter has presented a quantitative evaluation of water use for a winter wheat crop under two types of irrigation systems in Gassim: the modern sprinkler irrigation and the traditional open furrow systems. The fieldwork study identified significant differences between the TFs and CFs in terms of AWA and productivity, i.e. the values of AWA at the TFs was between 12663 and 18874 m^3/hectare/season and the productivity of wheat ranged from 1.6 to 2 ton/ha. On the other hand, in the CFs the AWA was 7100 and 9341 m^3/hectare/season and the productivity was 4.2 and 6.3 ton/ha.

It should be taken into account that the AWA values presented here, especially in the TFs, are subject to some uncertainty as they are partly dependent on information supplied by the farmers during fieldwork. This specifically relates to information on the frequency of irrigation during the season and the length of time for each irrigation, which some farmers may have been unable to supply with high accuracy. This has necessitated taking an average of each farmer's response, and this should be considered in the interpretation of the large differences in the amounts of AWA between the TFs, despite all farms having similar environments, e.g. soil and climate. Uncertainties also arise from the limited sampling programme. For this reason a range of values reflecting a 20% upper and lower limit of accuracy in estimates of AWA has been used.

In the study area, the average length of the growing season is about 130 days, so the total seasonal ET_O for the crop considered in this study is estimated to lie in the range of 406 mm/season for Farm 1 to 640 mm/season for Farm 4. Moreover, it has been found that commencing early sowing reduces CWR significantly. This is because the CWR consumption is affected by the higher temperatures and ET_O. CWR in the early and late seasons is estimated to be about 3038 m^3/ha/season and 5188 m^3/ha/season, respectively. In addition, all eight farms

require leaching of salts to counteract salinity of groundwater, ranging between 2% and 39% of CWR/season.

It was found that FWUE values are very low, they range from 0.09 to 0.17 kg/m^3 in the TFs, 0.59 and 0.67 kg/m^3 in the CFs. CWUE values are also low, ranging from 0.24 to 0.42 kg/m^3 in the TFs, and 0.84 and 1.42 kg/ m^3 in the CFs. Likewise, the results of estimates for IE confirm that the values are low, ranging from 19.6% at Farm 1 to 59.2% at Farm 7. There are differences in IE between the CFs and TFs but also considerable differences between the same farm types possibly resulting from a combination of measurement uncertainties and actual differences in practice. A discussion of the concept of IE has been presented with reference to recent ideas of system efficiency. Moreover, this study estimated the IS for each farm, which could be of key importance in achieving improved management of water resources for agriculture in the area.

It can be concluded that most farmers, especially in the TFs, are insufficiently versed in CWR, LR and IS, and their practices are mainly based on their experience. Therefore, in the study area, the farmers could be educated in matters pertaining to the accurate calculation of optimum water application.

Finally, the results of this chapter, particularly the results of ET_O and CWR will form the basis for calculating ET_O and CWR for the future with climate change in Chapter 7. In addition, the status of water use, and its efficiency in the study area, will also be of assistance when discussing the implications of climate change for water management in Chapter 7. However, before this, Chapter 6 presents scenarios of future climate in Gassim and Saudi Arabia.

Chapter Six: Climate Change Scenarios for Gassim

6.1 Introduction

The key issue in the current study concerns a comparison between the actual ET_O and CWR, which was investigated in Chapter 5 and scenarios for future ET_O and CWR in the Gassim area, which will be discussed in Chapter 7. Between these chapters, this chapter presents an investigation of climate change scenarios in the study area. The Earth's climate is now changing on account of the increasing atmospheric concentrations of GHGs which will probably have serious consequences on regional temperature and rainfall. The international community has become increasingly concerned over the last two decades as increases in global average temperature have continued, and although there will probably be more rainfall globally, not all regions will receive more, and some will almost certainly receive less (IPCC, 2001a).

Over the last 1000 years, the average global air temperature of the twentieth century was warmer than any other century. Warming has been observed over the last century by about 0.6°C. The 1990s were the warmest decade in the last 100 years. Moreover, there is also evidence that rainfall patterns are changing, sea levels are rising, glaciers are retreating, arctic sea-ice is thinning and therefore, in some parts of the world, the incidence of extreme weather is increasing (Hulme et al., 2002)

This chapter describes the implications of two of the IPCC's SRES emissions scenarios (IPCC, 2000) for climate change in the Gassim area in Saudi Arabia. It investigates the differences between the two emissions scenarios from three climate models, in order to estimate the effects of increasing GHG emissions on the future climate in the area.
This chapter includes the following information and analyses:

- A description of the two GHG emission scenarios used in this study;
- A description of the three climate change models used in this study;
- Assesses the ability of climate models to simulate the climate of the present via comparison between GCMs and observations.
- An outline of climate change in Saudi Arabia;
- A detailed analysis of future climate change in Gassim for the periods 2010-2039 and 2070-2099;
- A detailed analysis of daily Tmax and Tmin extremes and DTR in Gassim;
- The chapter ends with a discussion of the most significant results regarding insight into the expected range of climate change in the study area.

6.2 The GCMs Used for Study

For the purposes of investigating and understanding the future climate of the Gassim area, the study is conducted using the baseline observed climate of 1971-2000. These observed data are resolved into daily time-steps for temperature, and into monthly time-steps for rainfall, relative humidity, wind speed and sunshine duration. Climate changes are then estimated from simulations using three GCMs run under the two GHG emission scenarios, A2 and B2 proposed by the IPCC (2001), and these changes are applied to the baseline climate in order to create potential future climates (see Section 3.3.2).

6.3 Climate Change Scenarios

For a better understanding of the various processes that govern the global climate system, and in order to make climate change predictions, scientists have developed

climate simulation models over the last 20-25 years. The definition of a climate model is:

> *‘‘a numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties…. Climate models are applied, as a research tool, to study and simulate the climate, but also for operational purposes, including monthly, seasonal and interannual climate predictions’’* (IPCC, 2001a, p.788).

While the definition of scenarios is:

> *‘‘plausible descriptions of how things may change in the future [...] Scenarios contain plausible estimates of future changes in, for example, economic performance, population patterns and forms of governance [...] Scenarios can provide a range of possible future greenhouse gas emissions as inputs to global climate model experiments’’.* In other words, scenarios represent alternative projections of a potential future (Hulme et al., 2002, p.2).
>
> IPCC (2000, p.31) identified a scenario as *‘‘a description of a potential future, based on a clear logic and a quantified storyline’’.*

6.3.1 The SRES Emissions Scenarios

The IPCC Special Report on Emissions Scenarios (SRES) is a new set and range of emissions scenarios, which were used in the Third Assessment Report (TAR). The scenarios used in this study are two of four different scenario families. Each one describes a different world developing over the 21st century. Due to the uncertainties surrounding predictions in climate change, the researcher used these two scenarios specifically to assess a range of impacts of possible climate change on the study area; A2 and B2 climate change scenarios, with the HadCM3, CGCM2 and ECHAM4 GCMs. The two scenarios are described in Box 6.1, based on the IPCC (2000).

Box 6.1 The SRES Emissions Scenarios

The SRES A2 Family
The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines (IPCC, 2001b, p.23).

The SRES B2 Family
The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 and B1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels (IPCC, 2001b, p.23). Table 6.1 summarizes a comparison between the two scenarios.

Scenario	**A2**	**B2**
Population (billion) 2100	↗ 15.1	↗ 10.4
Economy	↗	↗
Environment	↘	↗
Equity	↘	↗
Technology	↗	↗
Globalisation	↘	↘
Climate	↗	↗
Emissions	High	Low
CO_2 concentration (ppmv)	834	601
Global annual-mean temp. change (°C)	3.09	2.16
Range (°C)	2.12-4.41	1.45-3.14

Table 6.1: A qualitative description of the A2 and B2 scenarios (IPCC, 2001b, p.24) and (Source: IPCC-TGCIA, 1999, p.40).

Box 6.1: Summaries of the SRES emissions scenarios, adapted from Climate Change 2001: Mitigation. IPCC, 2000.

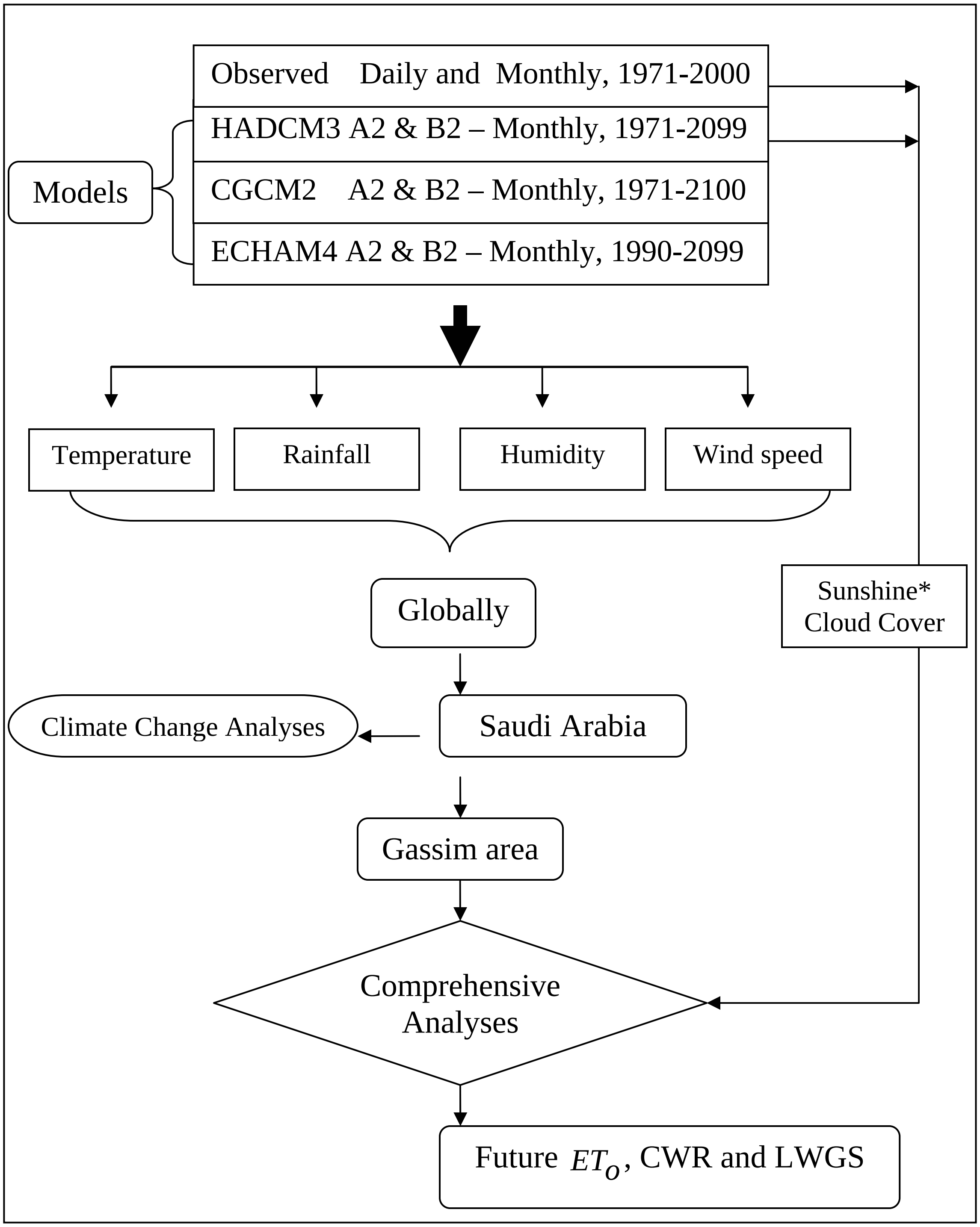


Figure 6.1: Outline of the processes used to deal with both the observed and the climate change data.

* Sunshine only used from observations.

6.4 GCM Comparison with Observations

Model validation procedures are a key component to create a reliable relationship between a simulation of current climate by the GCM and the observed climate and hence evaluation of future climates (see for example, Goodess, 2000; Doherty, 1999 and Hulme, 1999). Addiscot et al. (1995) indicated that validation is a significant step in model verification. The aim of this section is to assess the suitability and ability of the three GCMs to simulate climate variables in the study area against observed climate data in order to guide their use in climate change projections. IPCC (2001a) stated that coupled models could provide credible simulations of the present annual average climate. This approach involves comparing GCM simulations that represent present-day conditions (baseline climate period) to observed climate values in order to check the validity of the GCMs in Saudi Arabia and also in the study area. In terms of the study area, the observed and GCM climate data were projected onto one grid that represents the study area for the baseline climate, which is 1971 to 2000.

6.4.1 Annual Temperature in Saudi Arabia

The ability of the three GCMs to reproduce the observed average annual temperature is investigated. The average observed surface air temperature in Saudi Arabia is shown in Figure 6.2. The map-scale is drawn at three degree intervals between <0°C and >30°C. Observed average annual temperature patterns are generally uniform. Temperature is influenced by latitude and elevation, so colder temperatures can be seen to the north of Saudi Arabia as a consequence of latitude, and influence also can be seen of the mountain regions in the southwest. The overall average annual temperature ranges from 15° to 30°C. For comparison, the GCM spatial patterns in the control simulations are shown in the same figure. The overall patterns of temperature over Saudi Arabia are in general reproduced well by

all three models. HadCM3 produces a temperature range between 18° to 30°C, CGCM2 between 15° to 27°C and ECHAM4 between 15° to 30°C. It can be seen that in general HadCM3 is warmer by about 3°C, and the converse is true for CGCM2 and ECHAM4, which are both colder by about 3°C.

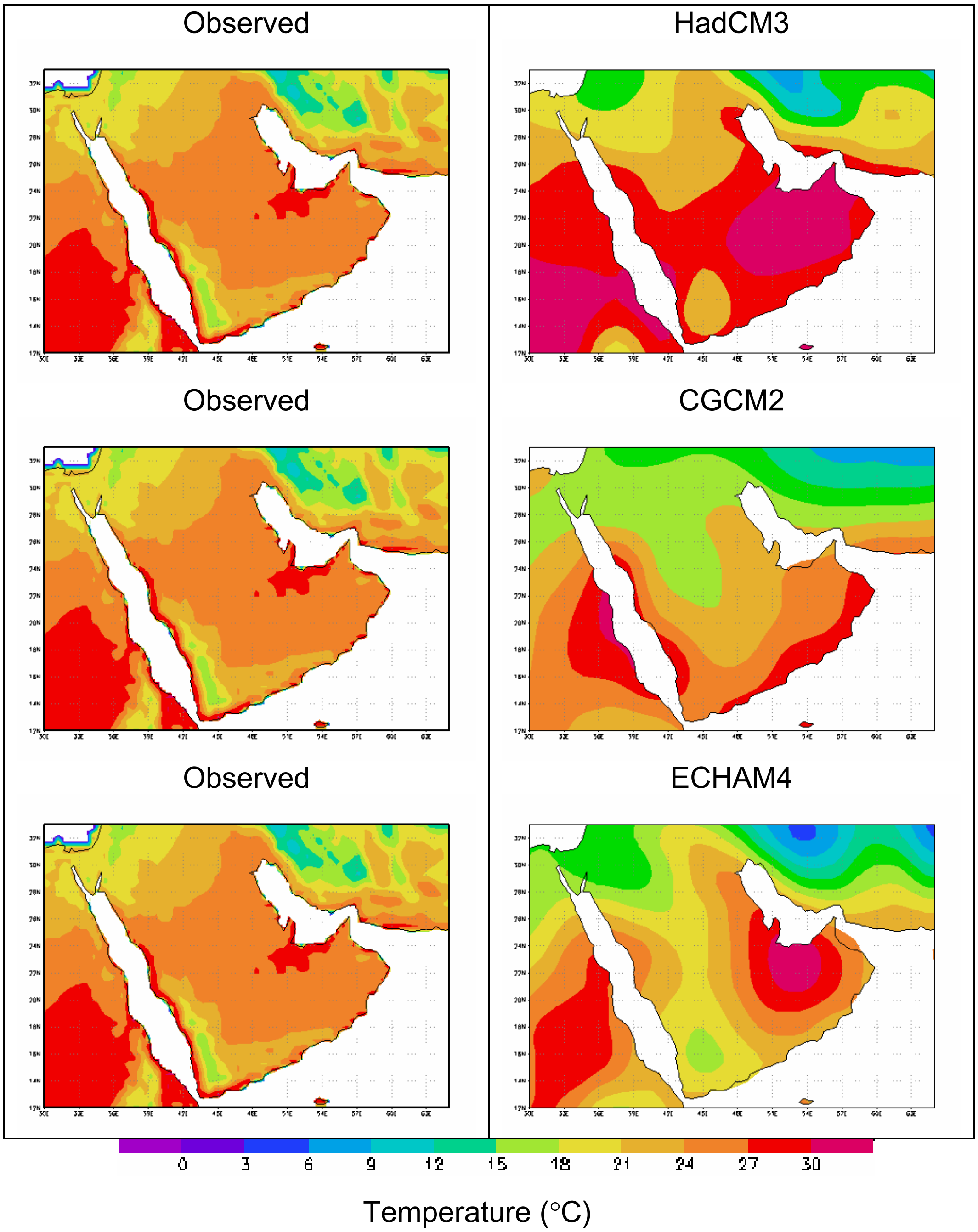


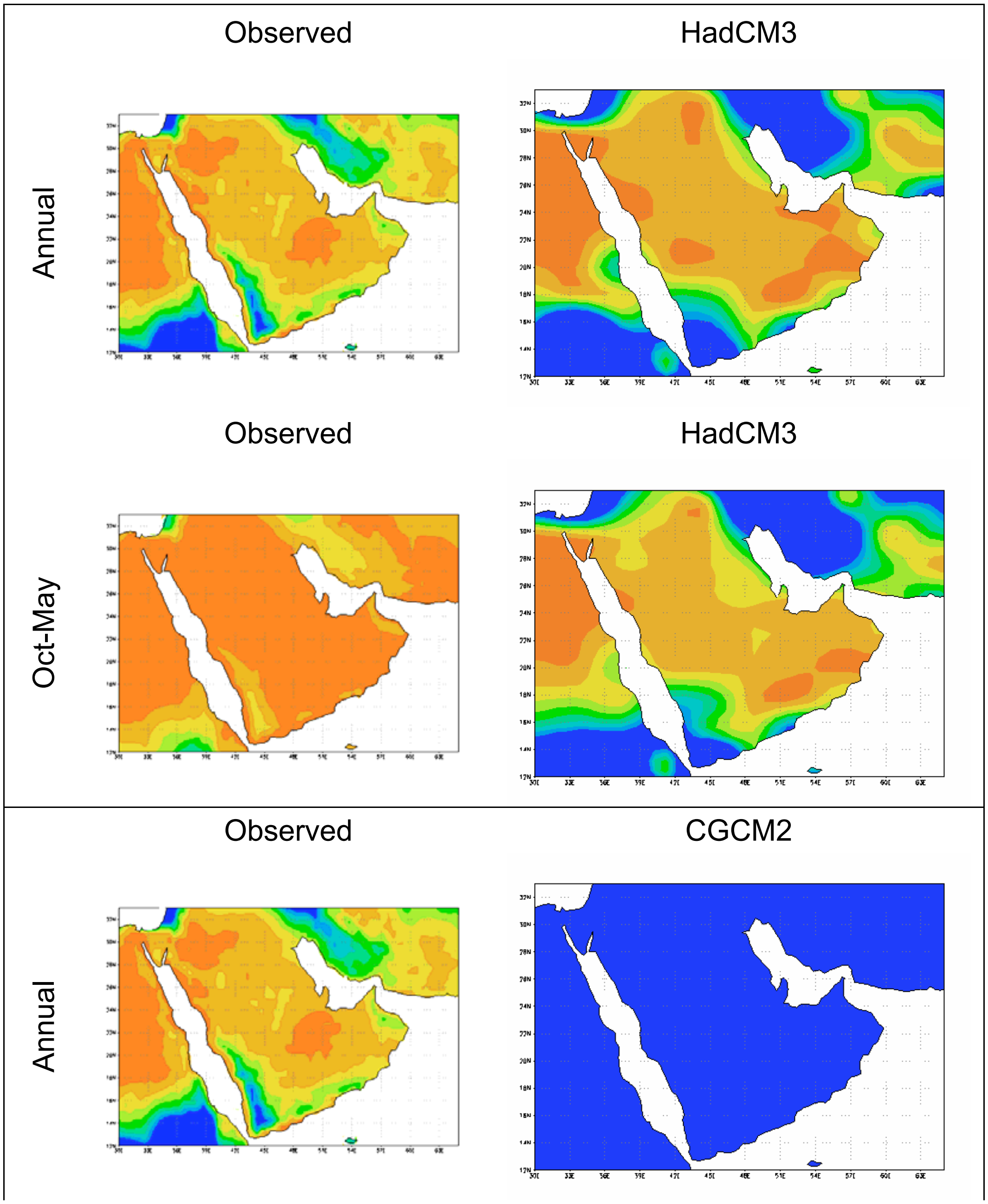
Figure 6.2: Difference between GCM simulation (1961-1990) and observed (1971-2000) average annual temperatures in Saudi Arabia.

6.4.2 Annual Rainfall in Saudi Arabia

In terms of rainfall Figure 6.3 shows observed and simulated annual and wet season (October-May) rainfall over the control period. Firstly, the patterns of annual observed rainfall range between 0 to 400 mm/year. It is clear that the region of mountains in the south-west receives more rain than any other part of the country. The highest rainfall reaches more than 400 mm/year, whereas, most of the country receives less than 100 mm/year on average. In relation to the wet season nearly all of the country receives no more than 50 mm on average, except the south-west of the country, where the range is from 50 to 150 mm.

According to the GCM simulations, the annual rainfall ranges from 0 – 400 mm for HadCM3, 0 to 250 mm for ECHAM4, and >400 mm for CGCM2. Generally, HadCM3 displays similar patterns and shows greater agreement with the observations, followed by ECHAM4 which gives an underestimate. In terms of the wet season ECHAM4 shows better agreement than the other models, while HadCM3 overestimates by about 50 mm.

The greatest differences in annual and wet season rainfall over the whole country are produced by CGCM2 which overestimates by about 300 mm annually and in the wet season as well. In summary, two models (HadCM3 and ECHAM4) show good agreement with the observations of the annual and wet season rainfall over Saudi Arabia. Hulme et al. (1999) found that the performance of HadCM3 in simulating the observed average monthly global rainfall patterns over land areas is as good as the best of the IPCC DDC models. In general, models are successful in reproducing the annual average temperature and two of them in reproducing the general rainfall patterns in Saudi Arabia. However, they fail to reproduce its finer detail. Nevertheless, a validation appropriate for the purposes of this study helps to show how well the models do simulate the observed climate in Saudi Arabia and gives some basis for comparing the reliability of their future scenarios.


Observed
HadCM3
Annual
Observed
HadCM3
Oct-May
Observed
CGCM2
Annual

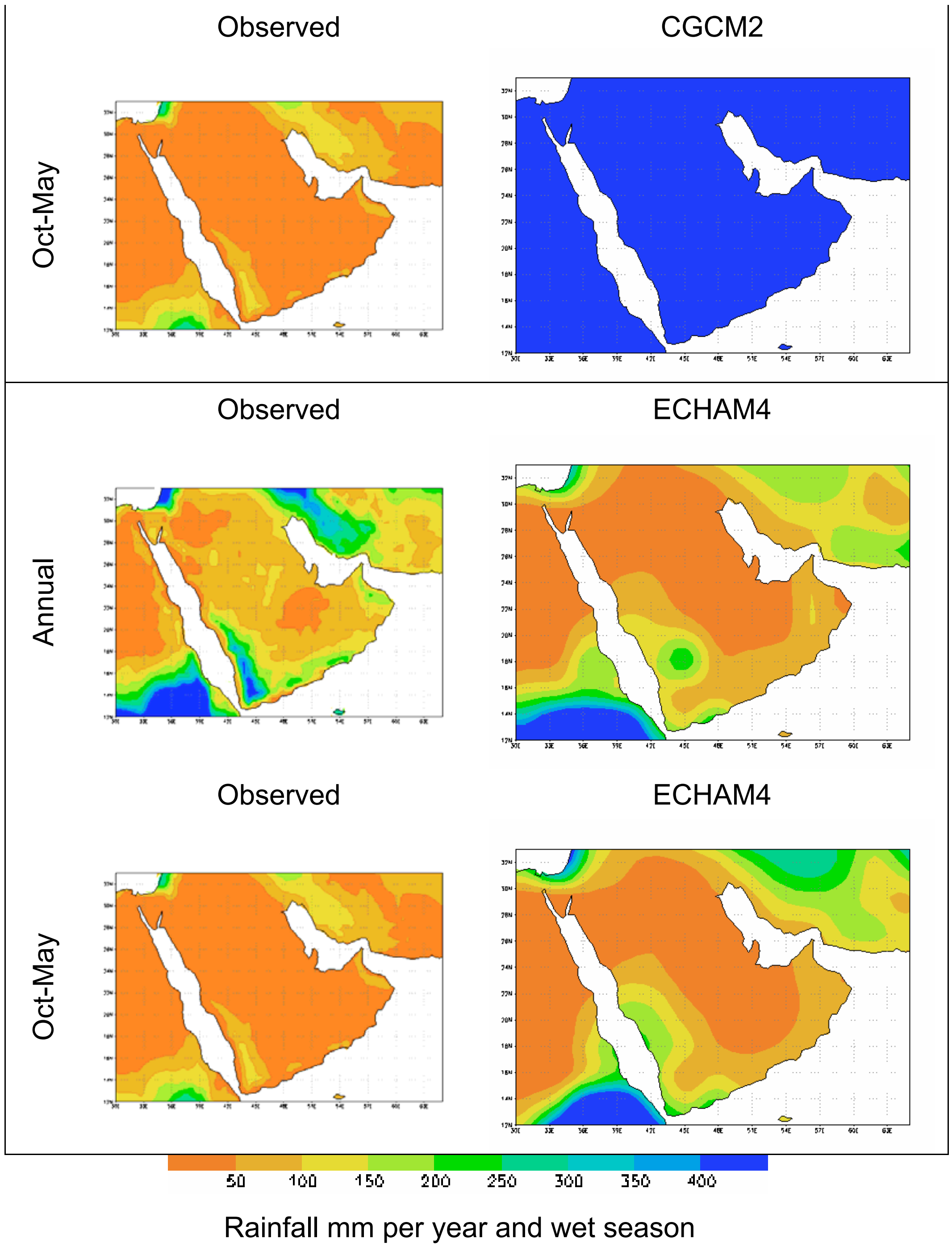


Figure 6.3: GCM simulation (1961-1990) and observed (1971-2000) total annual and wet season rainfall in Saudi Arabia.

6.4.3 Temperature in the Study Area

This section compares the three GCMs with observation for Gassim. GCM output for one grid box over-lying the study area is used for this comparison. This makes it a much harder test because model simulations are most accurate at larger spatial scales (i.e., hemispheric or continental), but at regional scales their skill is lower (IPCC, 2001a). Figure 6.4 compares monthly average temperatures for the Gassim area between observed and GCM data for the period 1971-2000. Two GCMs, HadCM3 and ECHAM4, have temperature patterns in close agreement with the observations. HadCM3 simulations have a slight cold bias in all months, except February and March. ECHAM4 simulations have a slight cold bias in all months, except in the summer. These biases are generally greater in the CGCM2 simulation, which shows Gassim temperatures to be substantially colder than the observed data in all seasons, and especially in the winter months.

To summarize, the annual difference between the observed temperature and HadCM3 and ECHAM4 simulations is about -0.5°C and -0.4°C, respectively. This means that both models show good agreement with the observations. The difference with CGCM2 is about 8.8°C and therefore shows poor agreement.

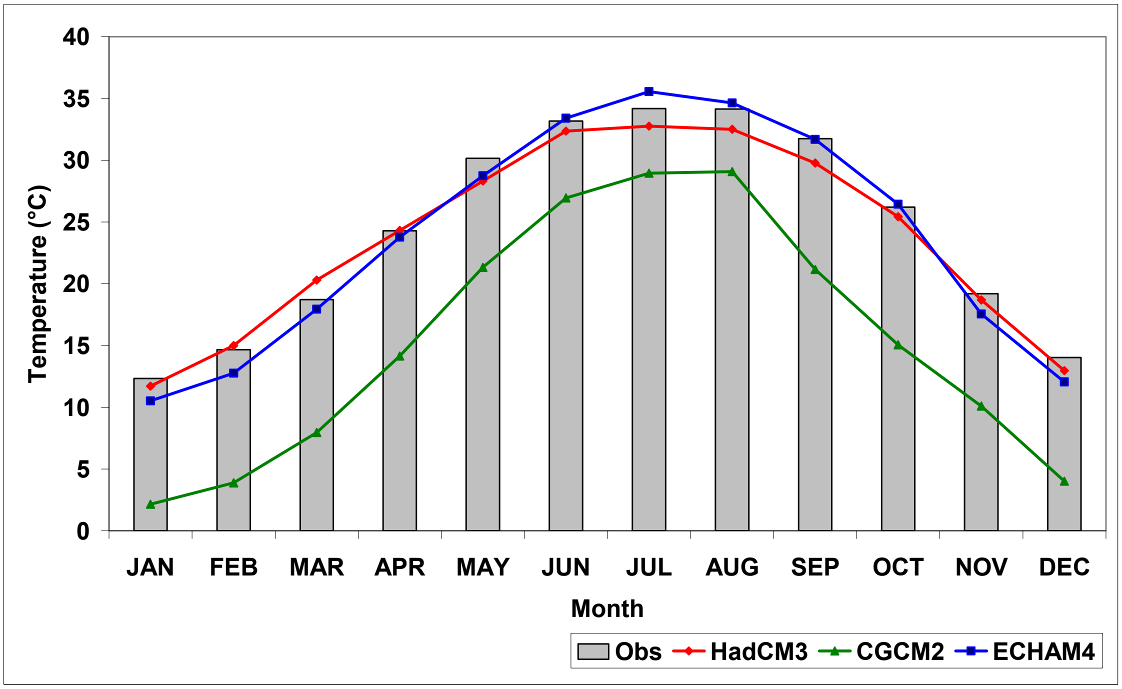


Figure 6.4: Difference between simulated and observed average monthly temperatures in the Gassim area over 30 year period 1971-2000, for observations and HadCM3, CGCM2 and ECHAM4.

6.4.4 Rainfall in the Study Area

In terms of rainfall, the level of agreement between the observations and the GCM output is variable. IPCC-TGCIA (1999) and other studies have reported that rainfall is more variable and more difficult to model than regional temperature. Figure 6.5 depicts rainfall over the study area from the observations and GCMs. HadCM3 and ECHAM4 are very different to the observations, as both models underestimate rainfall by -9.5 mm/month throughout the year, except the summer season, September, and October, which show good agreement. In general, both models depict the Gassim area to be too dry. On the other hand, CGCM2 simulations almost produce good agreement in winter, and from July until October.

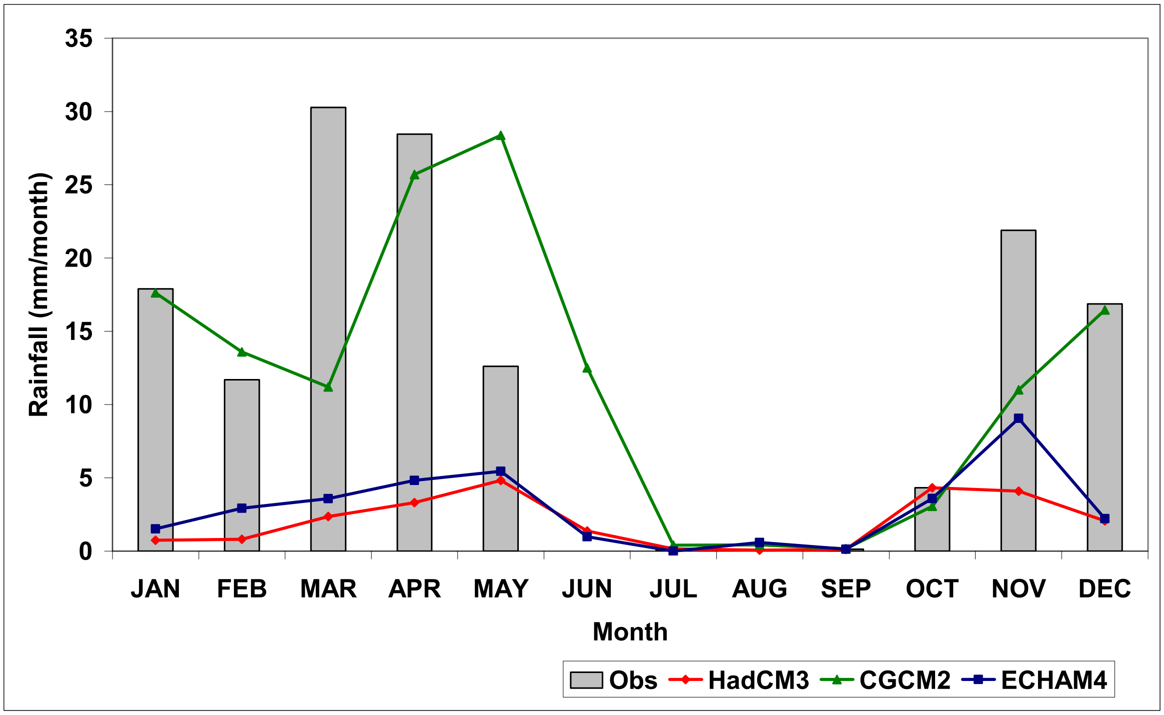


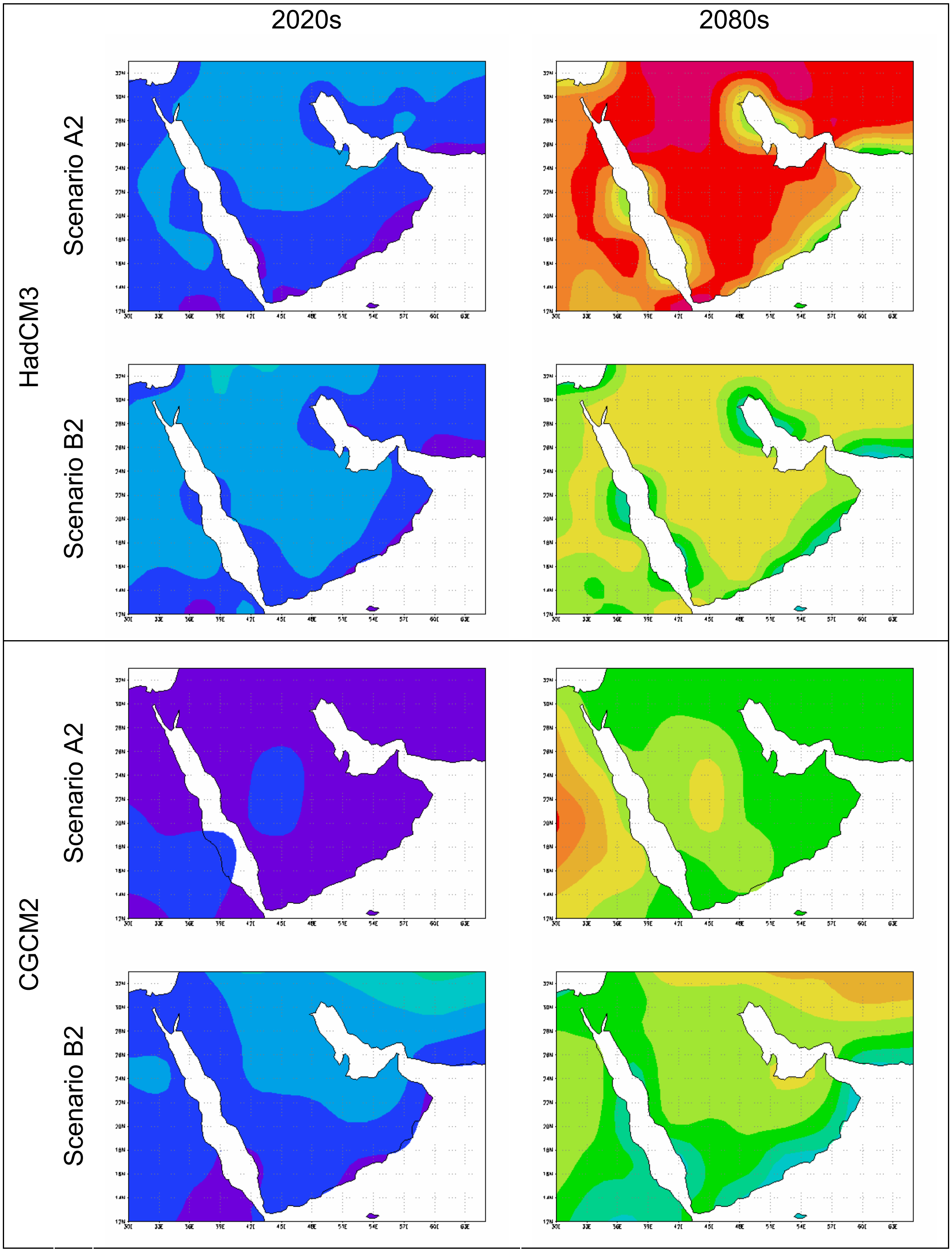
Figure 6.5: Simulated and observed average monthly rainfall in the Gassim area over the 30 year period 1971-2000, for observations and HadCM3, CGCM2 and ECHAM4.

6.5 Future Climate Change Scenarios in Saudi Arabia

6.5.1 Future Changes in Average Temperature

Figure 6.6 depicts the average annual temperatures simulated for Saudi Arabia by the three GCMs, under both of the chosen emission scenarios, for two 30 year time slices (2020s and 2080s), relative to the control period of 1971-2000. For example, by the 2020s, annual warming ranges from about 0.4° to 1.6°C across Saudi Arabia, whereas by the 2080s annual warming ranges from about 2° to 4.8°C. The major feature observed in Saudi Arabia is a greater warming in the centre and northeast (Figure 6.6). This warming is considerably greater in HadCM3 with A2 by the 2020s, and by the 2080s both HadCM3 and ECHAM4 show this tendency under scenario

A2. As expected, scenario A2 is warmer than scenario B2 in HadCM3 and ECHAM4 by the 2080s, whereas scenario B2 is very slightly warmer than A2 in all GCMs in the 2020s.



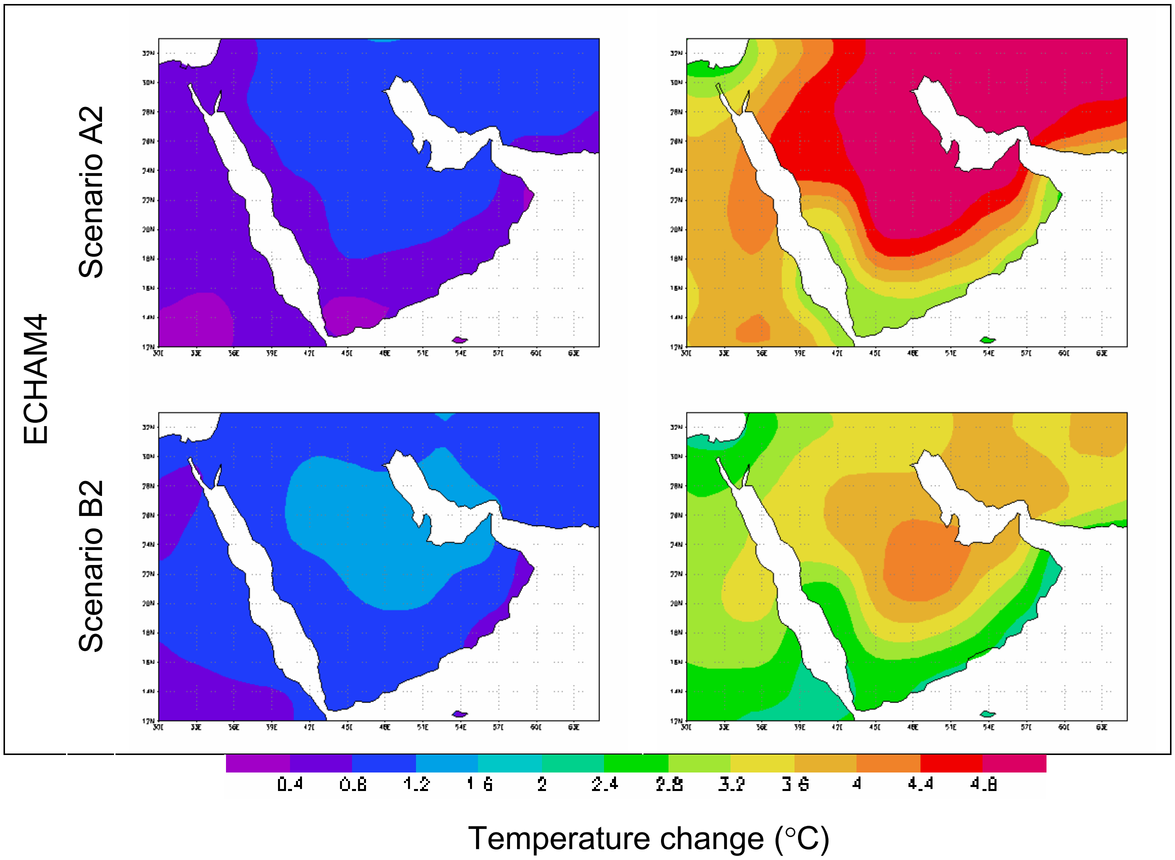


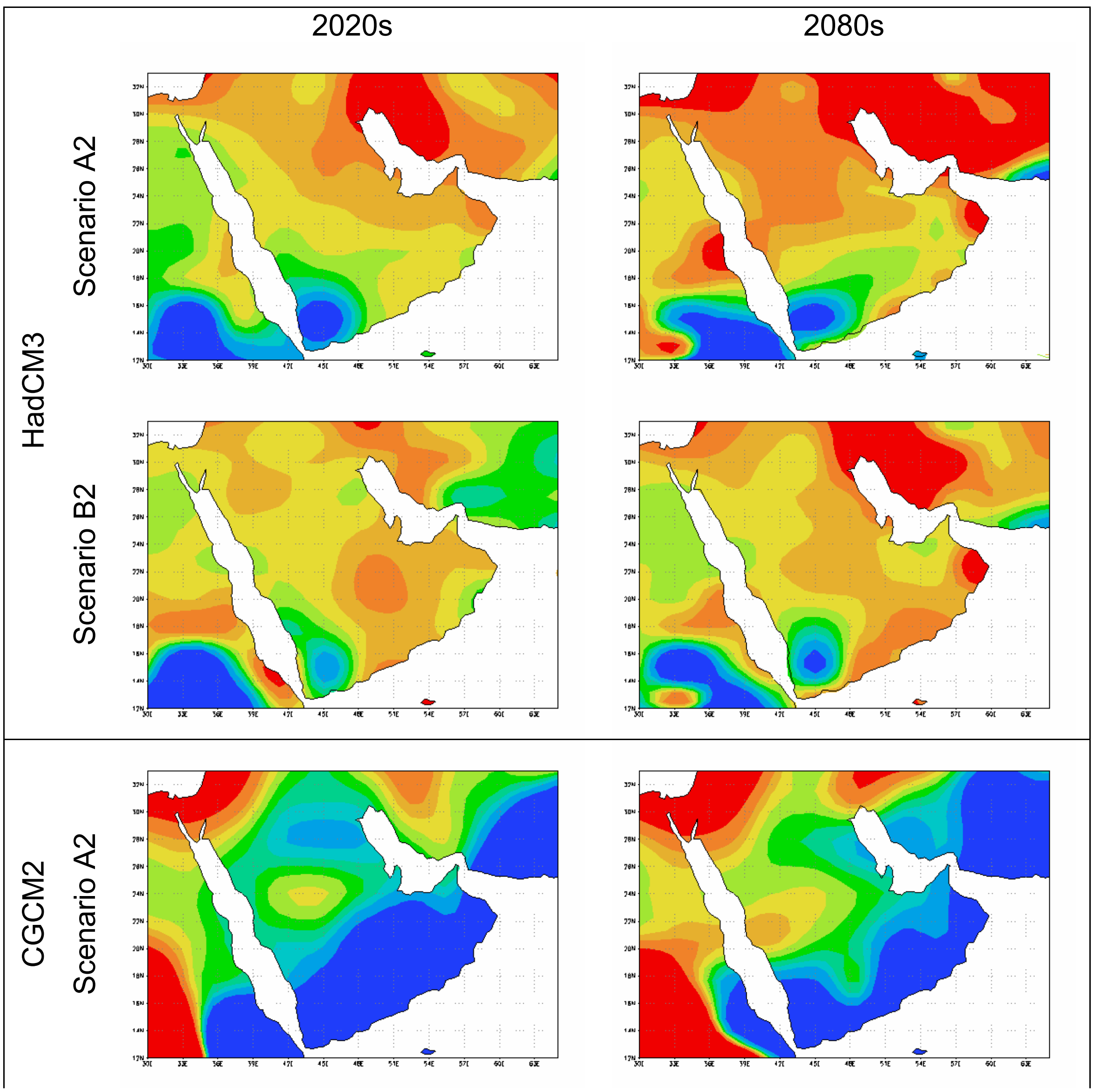
Figure 6.6: Changes in average annual temperature relative to the control period of 1971-2000, for 30-year periods centred on the 2020s and 2080s, for the three GCMs under two emission scenarios over Saudi Arabia.

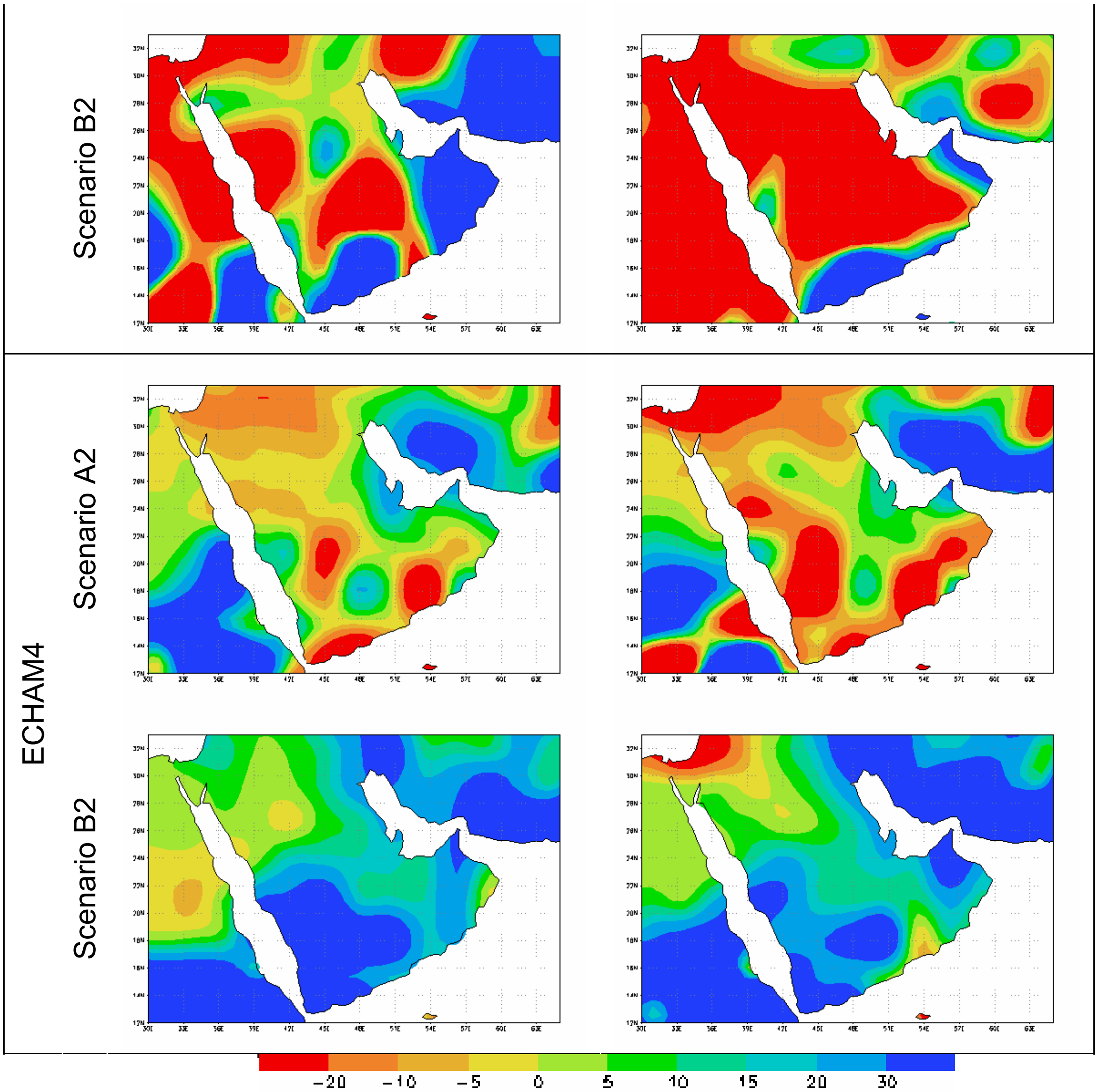
6.5.2 Future Changes in Average Rainfall

In contrast to temperature, the patterns of change for annual rainfall exhibit no clear trends, whether spatial or temporal. Figure 6.7 shows the simulated changes in rainfall over Saudi Arabia for all three GCMs, under both emission scenarios, for the 2020s and the 2080s. This shows, in general, that the differences in rainfall range from -30 to 40 mm/year, relative to the control period of 1971-2000. The greatest positive differences in rainfall are generated by ECHAM4, under B2 scenario for both periods over most of the country, especially in the south (ranging from 0 to 40

mm). In addition, CGCM2 with A2 scenario for two periods shows increases ranging from 0 to 40 mm. In contrast, the largest decrease is simulated by CGCM2 under scenario B2 for the 2080s (-30 mm).

In summary, CGCM2 scenario B2 for the 2080s and HadCM3 under both scenarios for the two periods simulate more extensive drying, whereas ECHAM4, under both emissions scenarios and CGCM2 under scenario A2 simulate more extensive wetting, for both periods.





Rainfall mm/year

Figure 6.7: Changes in average annual rainfall relative to the control period of 1971-2000, for 30-year periods centred on the 2020s and 2080s for three GCMs under two emissions scenarios over Saudi Arabia.

6.6 Future Climate Change Scenarios for Gassim

The study area is represented in each GCM by output for a single grid box, which was extracted from the global files (Figure 6.8). The development of these climate scenarios also used observations from Unizah station. As in the previous section, climate change scenarios were produced for two study time horizons, defined as the 2020s (2010-2039), and the 2080s (2070-2099). In the following, each variable for each GCM is presented, and expressed as monthly average values. The baseline climate is 1971-2000, and the changes were calculated such that temperature for example, were a product of:

(Average 30-year model future temperature – average 30-year model baseline (control) temperature) + observed baseline temperature).

Therefore, the variability of temperature and rainfall, remains the same as in the observations, but the average is different. These approaches have been developed because climate model results are still too inaccurate on a regional scale to be used directly (Reilly et al., 2000).The two time slices were chosen partly because these periods are commonly used by other researchers (particularly Hulme et al., 2002) and because they provide a near term picture (2020), and a longer-term future perspective, where the changes may be much greater.

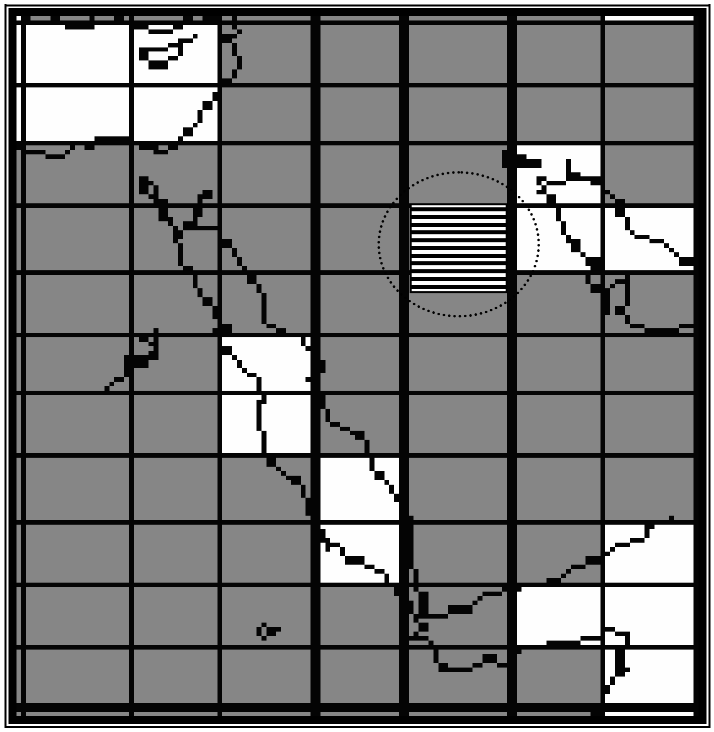


Figure 6.8: Map of the grid box that represents the study area with HadCM3 grid (the Climate Impacts LINK Project, Web site - http://www.cru.uea.ac.uk/link/hadcm2/afr.html. 2004).

6.6.1 Future Changes in Average Temperature

Observed average annual temperatures and the GCM simulated temperatures for the 2020s and 2080s with the SRES A2 and B2 emissions scenarios are shown in Figure 6.9, for the three GCMs.

The average changes in temperature (future minus control) are superimposed upon the 30 year observed record. Extrapolation of the observed linear trend in temperature 0.05°C/year is similar to the average projected warming for the 2020s, and by the 2080s (scenario A2 for each model), whereas the observed linear trend is higher than warming in scenario B2. It should be noted that the regression line extrapolation of the trend is only for the purpose of comparing with the future rate of

warming and is in no way suggested to be predictive.

By the 2020s, all of the models suggest that the change in temperature, under both emissions scenarios, will not be large in comparison to the observed variability. By the 2080s, however, the differences in temperature changes are clear and significantly in excess of the observed levels of variability. Moreover, the A2 scenario produces greater increases in temperature than the B2 scenario with all three models. In addition, the temperature changes for the three models are consistent, indicating that the different emissions scenarios generate similar temperature changes by the 2020s, and also by the 2080s.

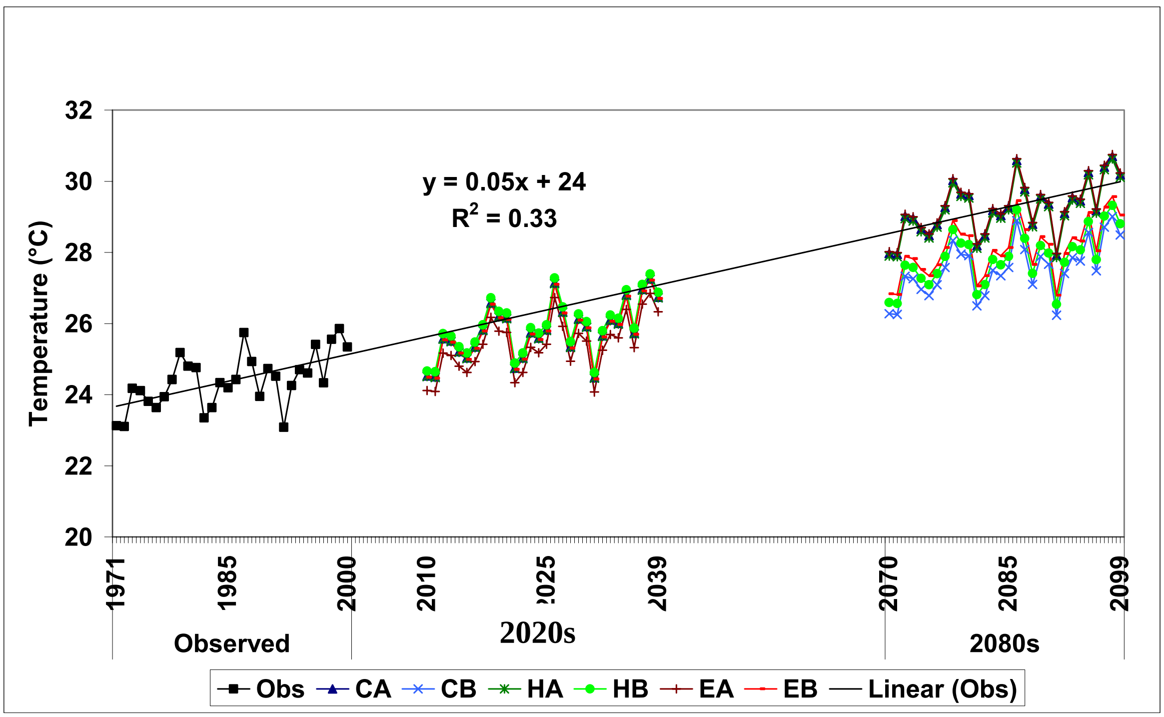


Figure 6.9: Changes in average annual temperature from the average 1971-2000 climate, for two 30-year periods centred on the 2020s and 2080s under two emission scenarios. (The linear trend line represents an extrapolation of the observed trend 1971-2000 for visual purposes only).

Key: C= **C**GCM2, H= **H**adCM3, E= **E**CHAM4, A= Scenario **A**2, B= Scenario **B**2.

Figure 6.10 shows the observed average annual temperature series and its 30-year average for comparison with the average temperatures in the 2020s and 2080s (24.2°C, 25.7°C and 28.5°C, respectively). By the 2020s, the warmest is HadCM3 under scenario B2 (25.9°C), but by the 2080s it is ECHAM4, with scenario A2 (29.3°C).

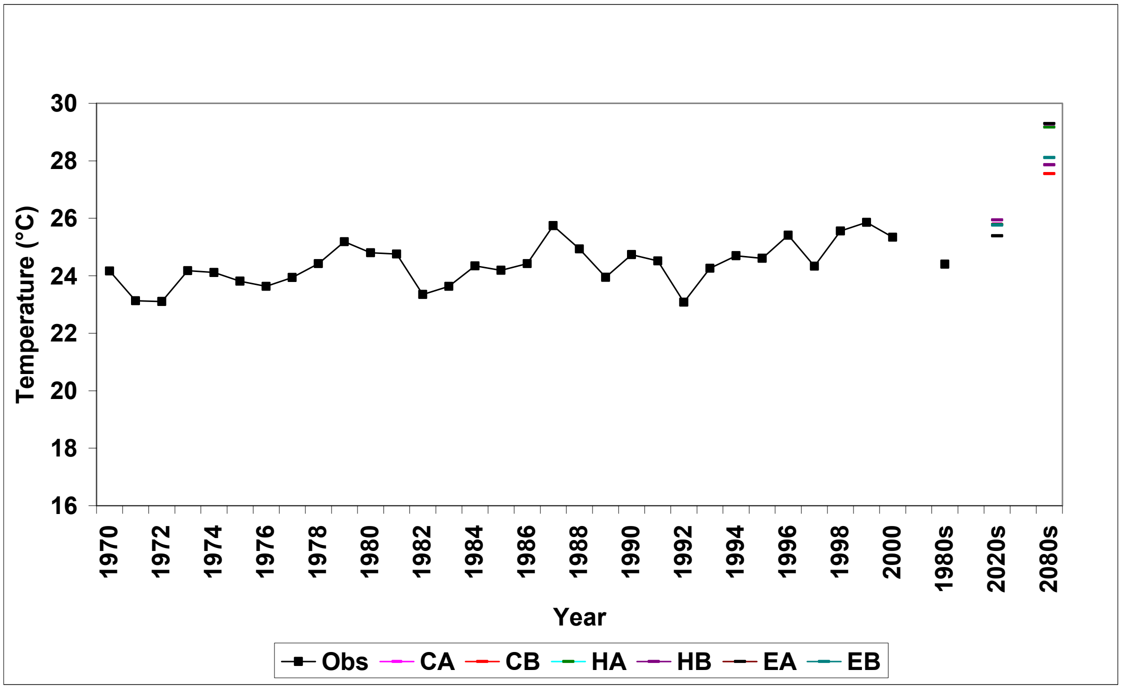


Figure 6.10: Observed and simulated 30-year average annual temperatures for the 1980s (time series of observations), the 2020s and the 2080s for three GCMs with two emissions scenarios.

Table 6.2 summarises the main changes in average temperature. The warming for the three models is between 0.99°C and 1.54°C by the 2020s, and by the 2080s, the range is between 3.15°C and 4.89°C. HadCM3 scenario B2 produces the largest increase in temperature by the 2020s, whilst ECHAM4 scenario A2 produces the smallest increase. By the 2080s, ECHAM4 scenario A2 produces the greatest increase in temperature, and also with scenario B2, the smallest increase in temperature. These results indicate that the sensitivity of the climate warming over

Gassim is similar to the global average warming rates. For example, IPCC (2001a) indicated that area-averaged annual average warming would be about 5°C by the 2080s over the land regions of Asia. On a global scale, the average temperature increase for scenario A2 ranges from 1.3 to 4.5°C, while for the B2 scenario it ranges from 0.9 to 3.4 by the 2080s.

	Period	**Scenario**	**HadCM3**	**CGCM2**	**ECHAM4**
Temperature changes (°C)	the 2020s	A2	1.38	1.40	0.99
		B2	1.54	1.38	1.36
	the 2080s	A2	4.77	4.84	4.89
		B2	3.46	3.15	3.71

Table 6.2: Summary of changes in the Gassim temperatures by the 2020s and the 2080s, for three models and with two emission scenarios. Changes are calculated with respect to the 1971-2000 average.

On monthly time scales, Figure 6.11a indicates that, by the 2020s, for all models and under both scenarios, the average monthly temperature in the study area is higher than that observed in each month. The climate scenario B2, based on HadCM3 has the highest average monthly increase (1.5°C). In contrast, A2, with ECHAM4, has the lowest average monthly air temperature increase (1°C). It can also be noted that the changes from July to October exhibit greater increases than the other months.

Figure 6.11b shows that, by the 2080s, A2 emissions with ECHAM4 give the highest average monthly increase (4.9°C). In contrast, B2 emissions with CGCM2 give the lowest average monthly air temperature increase (3.2°C). In general, when comparing the observed monthly temperature to those projected by the models, only small differences are in evidence by the 2020s, but these differences are more pronounced by the 2080s.

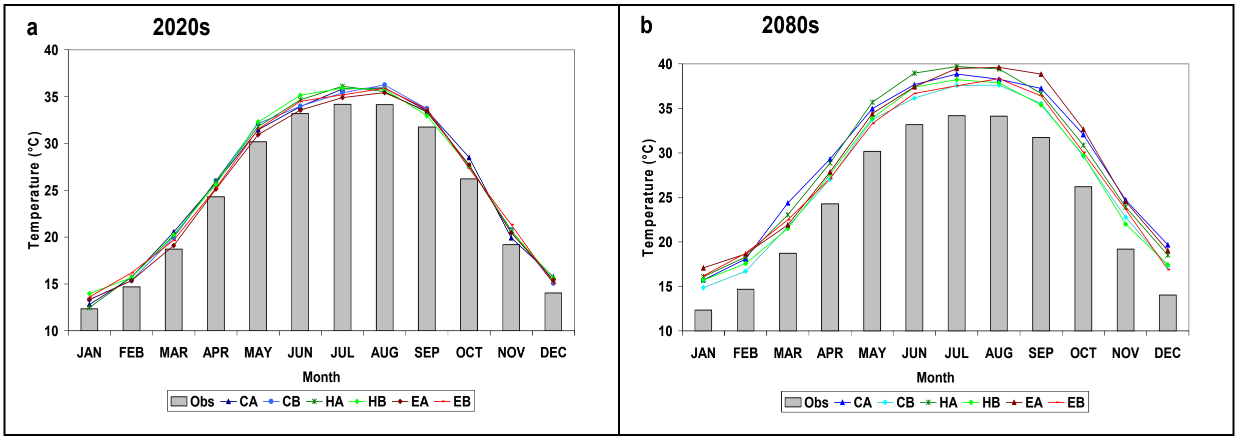


Figure 6.11: a and b Projected monthly temperatures based on the three climate models under the two emission scenarios by the 2020s (a) and the 2080s (b).

6.6.2 Future Changes in Average Rainfall

Figure 6.12 shows the time series for annual rainfall under A2 and B2 emissions scenarios for each climate model. In general, the patterns of change for each model are quite similar and there are no significant differences between the models for either the 2020s or the 2080s. Moreover, the observed linear trend of total annual rainfall (extrapolated into the future), is clearly greater than the changes simulated by the three models, whether during the 2020s period or the 2080s period. It should again be noted that the regression line is not intended as prediction but is intended for comparative purposes between the current trend and the model simulations (the observed trend is quite sensitive to the period used for its calculation).

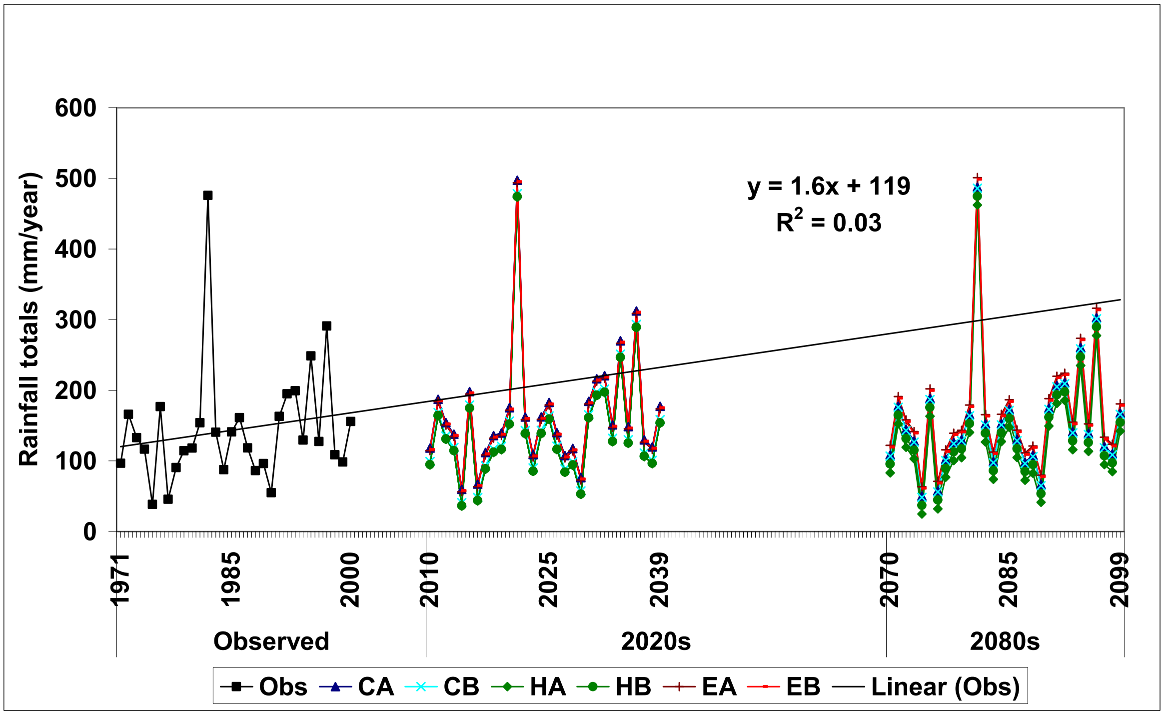


Figure 6.12: Changes in annual rainfall, observed and simulated, predicted by the three climate models. (The linear trend line represents an extrapolation of the observed trend 1971-2000 for visual purposes only).

Table 6.3 summarizes the future rainfall changes in Gassim. There is some discrepancy between HadCM3, which indicates a decrease, and the others, which indicate increases. In most respects, the results from CGCM2 lie between the results of the other two, producing increases in both the 2020s and 2080s. In both cases, the A2 scenario produces more rainfall than B2, and the changes are larger for both scenarios in the 2020s than in the 2080s.

In terms of a comparison with the baseline period, CGCM2 produces a little more rainfall in scenarios A2 and B2, by approximately 21 mm/year and 3 mm/year, respectively, by the 2020s, and by 12 mm/year and 10 mm/year, respectively, by the 2080s. On the other hand, ECHAM4 in the 2020s and the 2080s. produces significant increases in rainfall under scenarios A2 and B2, which are much larger than those of CGCM2. Compared with the baseline period, ECHAM4 produces

more rainfall under both scenarios, at approximately 18 mm/year and 20 mm/year, respectively, by the 2020s, and 25 mm/year and 23 mm/year, respectively, by the 2080s. Conversely, with HadCM3 scenarios A2 and B2, the rainfall decreases slightly, by about -3 mm/year and -2 mm/year, respectively, by the 2020s, and by about -14 mm/year and -1 mm/year, respectively, by the 2080s.

	Period	Scenario	HadCM3	CGCM2	ECHAM4
Rainfall changes (mm/year)	the 2020s	A2	-3	21	18
		B2	-2	3	20
	the 2080s	A2	-14	12	25
		B2	-1	10	23

Table 6.3: Summary of changes in Gassim rainfall by the 2020s and the 2080s, for three models and with the two emissions scenarios. Changes are calculated with respect to the GCM control period (1971-2000 average).

6.6.2.1 Monthly Changes in Rainfall

The simulated changes in rainfall exhibit both differences and similarities (Figure 6.13 a and b). By the 2020s there is very little change, except with CGCM2 (A2), which produces slightly more rainfall, at about +2 mm/month on average. By the 2080s (Figure 6.13 b) very slight increases occurs for CGCM2 and ECHAM4, at approximately 1 and 0.3 mm/month, respectively. HadCM3 produces little change in rainfall over the study area, ranging from -0.1 to -1 mm/month. To summarise, the monthly climate change scenarios show no significant change between the 2020s and the 2080s, but there are some changes between the months in both periods. The climate models suggest changes in temperature during the 21st century in Gassim that may have greater implications than the very modest changes in rainfall shown here. The following two sections briefly present changes in relative humidity and wind speed which are used in Chapter 7 to generate scenarios of future ET_O.

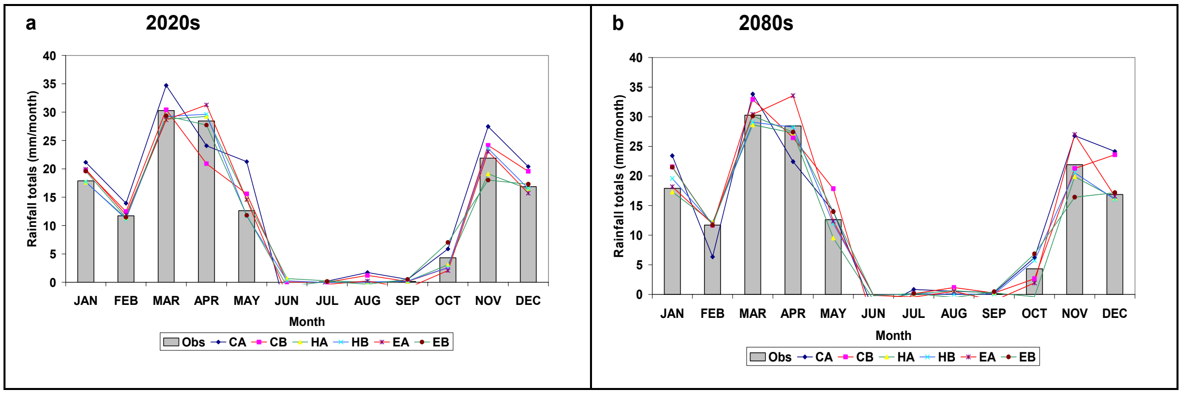


Figure 6.13: a and b Changes in rainfall (relative to the average 1971-2000 baseline) for the 30-year periods, centred on the 2020s and 2080s for the three models and with the two scenarios.

6.6.3 Future Changes in Average Relative Humidity

The scenarios of change in average relative humidity in Gassim show that by the 2020s the expected changes are very small, and range from +1% for CGCM2 with scenario B2 to -1% for HadCM3 with scenario A2. However, by the 2080s, the changes are larger and range from +6% with CGCM2 scenario B2 to -3% for HadCM3 scenario A2 (Figure 6.14). The future relative humidity values with CGCM2 under both scenarios and for ECHAM4 scenario B2 show increases, whereas HadCM3 and ECHAM4 scenario A2 show decreases.

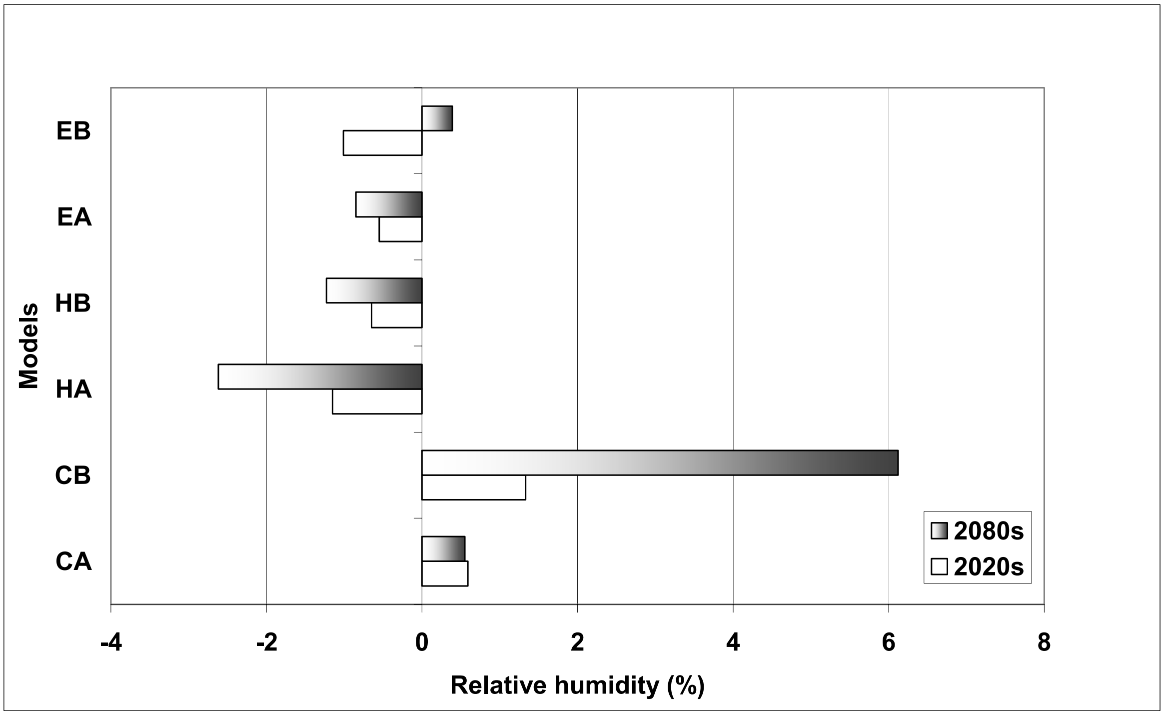


Figure 6.14: Changes in annual average relative humidity in Gassim for the three models under the two scenarios, by the 2020s and the 2080s, and relative to 1971-2000.

Figure 6.15a shows the changes for monthly relative humidity. By the 2020s, HadCM3 and ECHAM4 present no significant changes over Gassim, but slight increases are observed with CGCM2 in both scenarios. By the 2080s, the changes in relative humidity are more pronounced relative to the 2020s; in CGCM2 scenario B2 the average monthly relative humidity increases by about 6% especially in the wet season, while the other models generally indicate slightly reduced values (Figure 6.15 b). In all cases, the changes in relative humidity are different in all months.

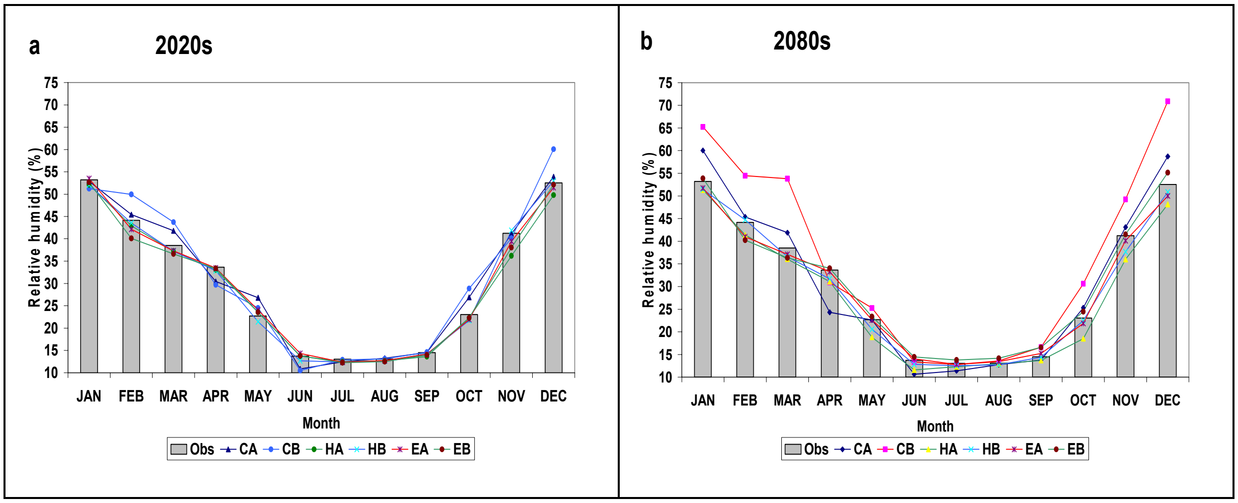


Figure 6.15: a and b Control and future monthly relative humidity, for the 2020s and the 2080s, with A2 and B2 emissions.

6.6.4 Future Changes in Average Wind Speed

By the 2020s, Figure 6.16a demonstrates that no significant changes occur in average monthly wind speed. The changes range from only +0.1 m/s for CGCM2 under scenario B2 to -0.07 m/s for HadCM3 under scenario A2.

By the 2080s, the changes range from +0.12 m/s for CGCM2 under scenario A2 to -0.12 m/s for HadCM3 under scenario A2 (Figure 6.16 b). It can be concluded that the changes in both periods from May to September are more pronounced than the rest of the months in each model but remain fairly insignificant.

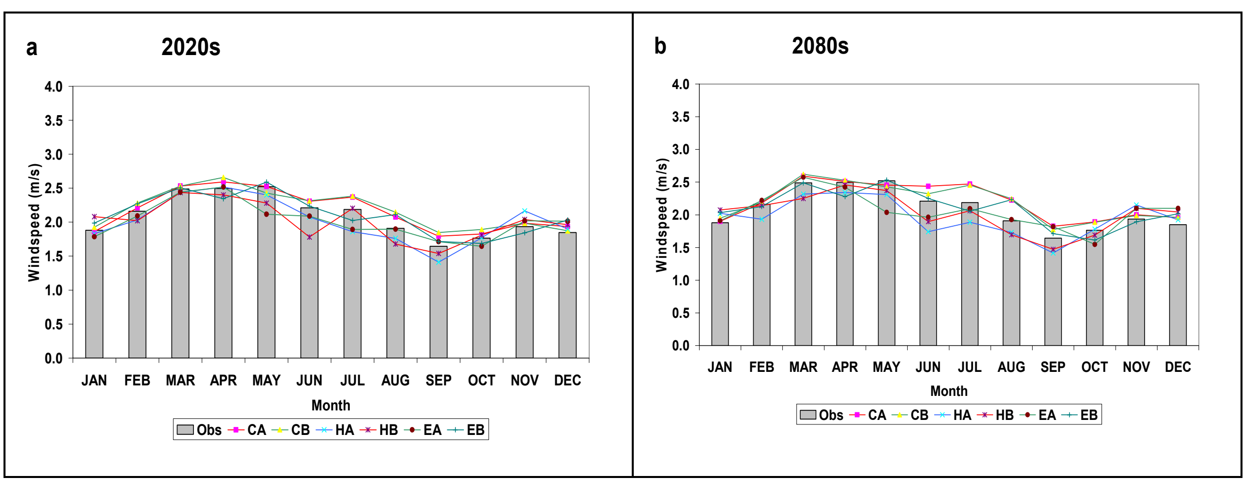


Figure 6.16: a and b Observed and simulated average monthly wind speeds by the 2020s and the 2080s, with A2 and B2 emissions.

Table 6.4 summarizes the annual changes in wind speed. HadCM3 under both scenarios and ECHAM4 under scenario A2 produce slight decreases in wind speed by the 2020s and the 2080s, whereas CGCM2 under both scenarios and ECHAM4 with B2 produce slight increases in both periods.

	Period	Scenario	HadCM3	CGCM2	ECHAM4
Wind speed changes (m/s)	the 2020s	A2	-0.07	0.08	-0.07
		B2	-0.07	0.10	0.03
	the 2080s	A2	-0.12	0.12	-0.03
		B2	-0.07	0.11	0.02

Table 6.4: Summary of changes in the Gassim wind speed by the 2020s and the 2080s, for the three models and with the two emissions scenarios. Changes are calculated with respect to the GCM control period 1971-2000 average.

6.7 Extremes in Daily Tmax and Tmin

The following sections examine daily Tmax and Tmin in the Gassim area, beginning with a change of emphasis with analysis of observed daily temperatures before presenting future changes. The aim of this section is to provide a more detailed analysis of the possible effects of higher frequencies of extreme temperatures in the area. Their implications are discussed in Chapter 7.

6.7.1 Observed Daily Temperature Extremes from 1971-2000

6.7.1.1 Annual Tmax, Tmin and DTR

Are observed temperatures in Gassim rising, falling, or showing any significant change or trend? This is answered by the following analysis, which reveals the presence of an increase in the average Tmax and Tmin during the period of study. More specifically, the observed daily Tmax and Tmin analyses indicate that the

1990s were the warmest decade in the full record, and that 1999 was the warmest year on record in Gassim (Figure 6.17). Figure 6.17 demonstrates that the increase in temperature in recent decades has involved a faster rise in daily Tmax than in Tmin and this has caused an increase in the average diurnal temperature range (DTR). The trend in Tmax for the duration of the record is about 0.7°C/decade, and the trend for the Tmin is approximately 0.3°C/decade, and as a result, the trend in the DTR is about 0.4°C/decade. It can be noted that most of the rise is in the last 10 years.

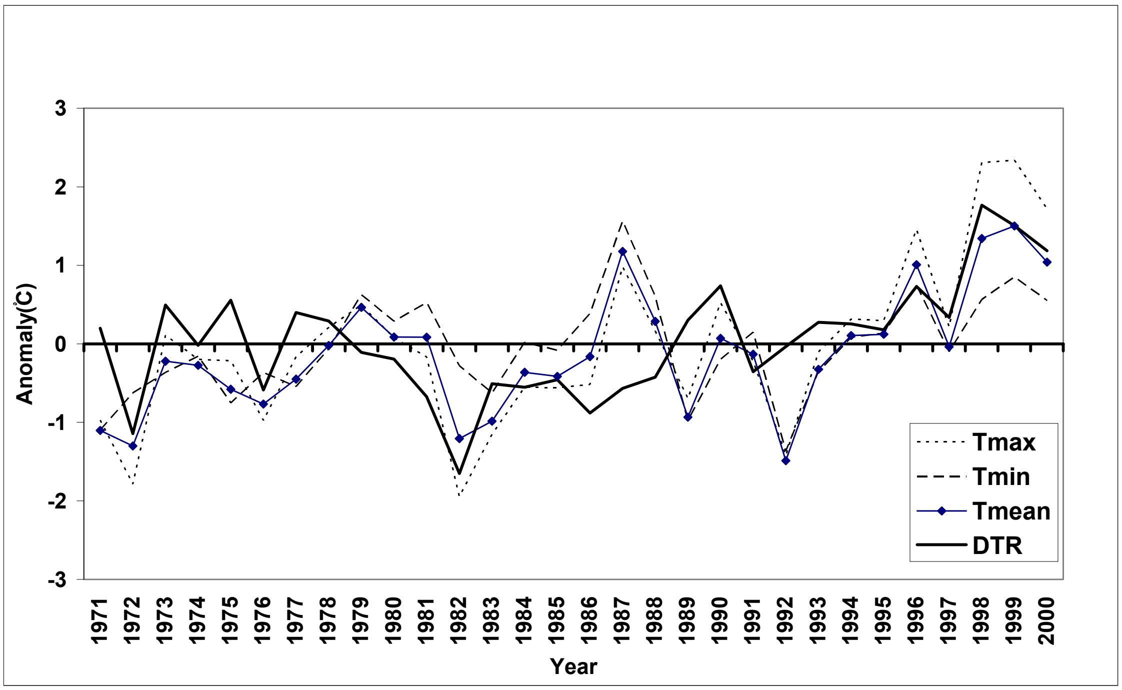


Figure 6.17: Anomalies (from 1971- 2000 average) of observed variations in annual Tmax and Tmin, and the DTR, in Gassim.

6.7.1.2 Tmax: Seasonal Analysis for Winter

Temporal variability in extreme temperatures in Gassim is investigated using the observed daily Tmax and Tmin with five indicators: 10th percentile[1] and 90th percentile of Tmax; 10th percentile and 90th percentile of Tmin; and the number of

[1] Percentile: Any one of the points dividing a distribution of values into parts, each of which contain 1/100 of the values (http://www.epa.gov/ttn/atw/nata/gloss1.html).

frosty nights (≤0°C). These indicators are based on daily data, and are useful for understanding changes in extremes and variability. The data were analysed for two seasons, winter and summer (December-January-February and June-July-August, respectively).

Figure 6.18 displays the number of days over 30 years (1971-2000) during the winter season with percentile thresholds below the 10th percentile of the daily Tmax, (14°C). The frequency of Tmax days below the 10th percentile has decreased very slightly; this is in agreement with the trend derived from the observed annual temperature. Figure 6.19 shows that no major changes are apparent in the number of days with thresholds above the 90th percentile of daily Tmax in winter (26.2°C). The year 1998 has the highest number of days above the 90th percentile (19 days). Consequently, the daily Tmax record over 30 winters shows a decrease in the frequency of very cold days in the study area, but no apparent trend in the number of very warm winter days.

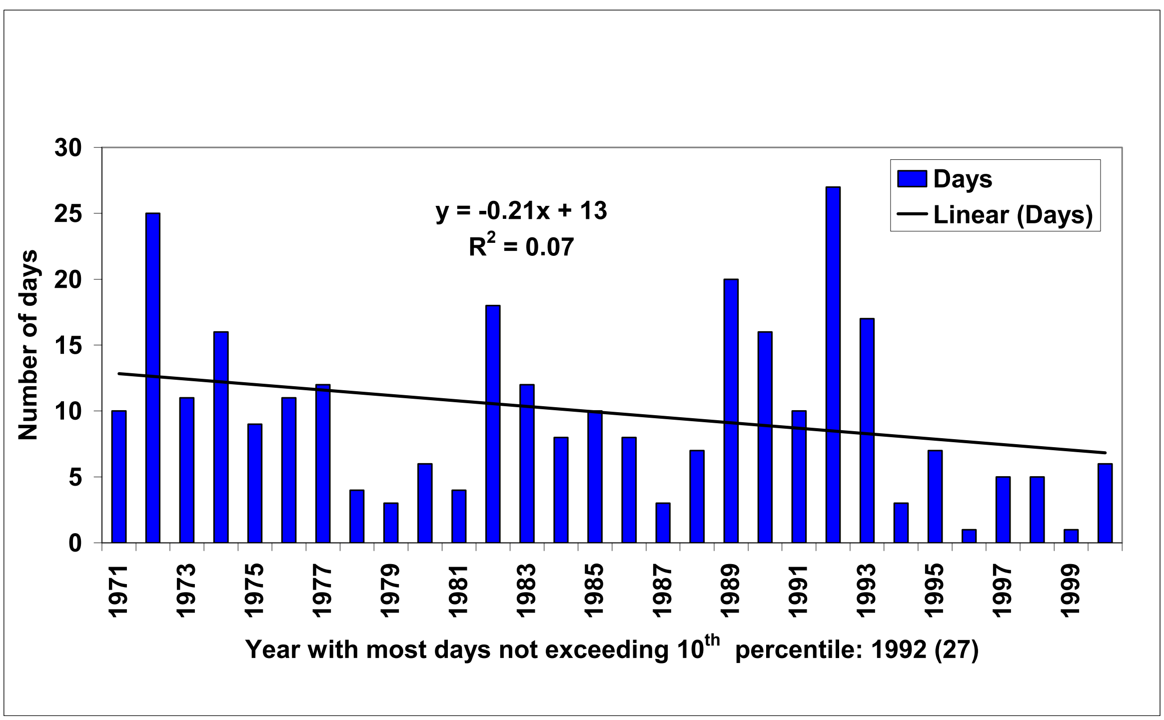


Figure 6.18: Counts of days each year, 1971-2000, in Gassim with thresholds below the 10th percentile of the winter (DJF) maximum daily temperature.

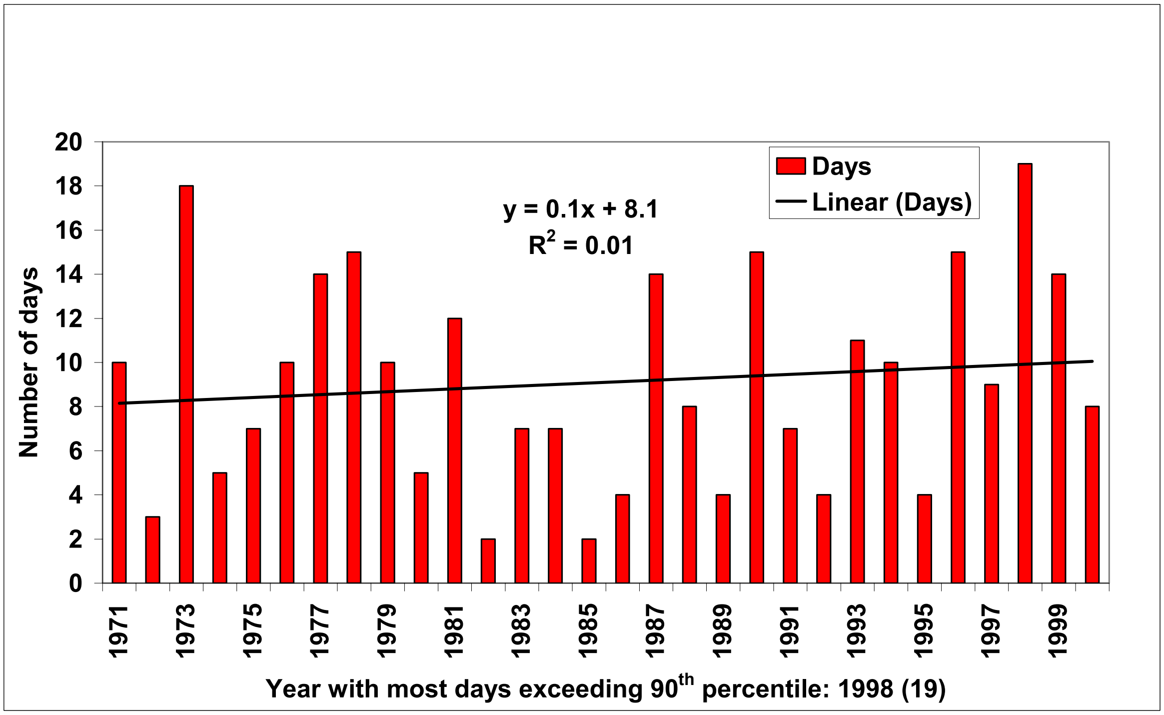


Figure 6.19: Counts of days each year, 1971-2000, in Gassim with thresholds above the 90th percentile of the winter (DJF) maximum daily temperature.

6.7.1.3 Tmin: Seasonal Analysis for Winter

With regard to the Tmin during winter, Figures 6.20 and 6.21 show that there are no tendencies or marked changes in the number of days that have extreme temperatures below the 10th percentile (2.8°C) or above the 90th percentile (12°C) 1989 has the highest number of days below the 10th percentile (36 days), while 1979 and 1981 have the highest number of days above the 90th percentile (22 days each).

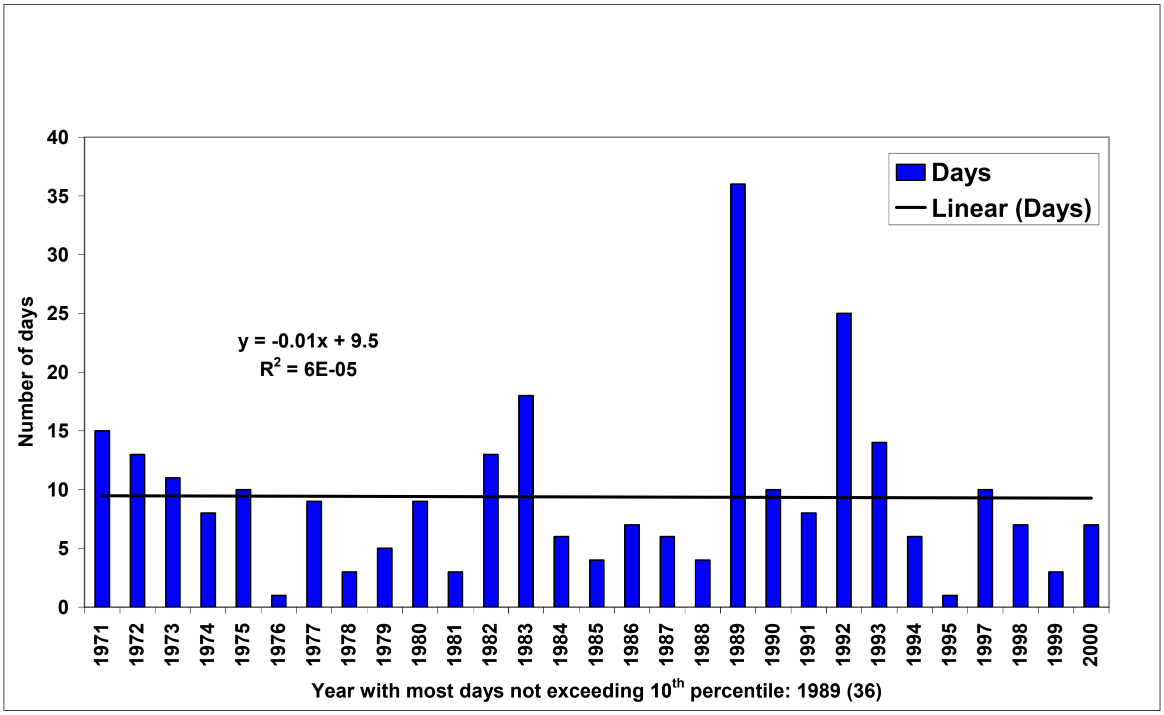


Figure 6.20: Counts of days each year, 1971-2000, in Gassim with thresholds below the 10th percentile of the winter (DJF) minimum daily temperature.

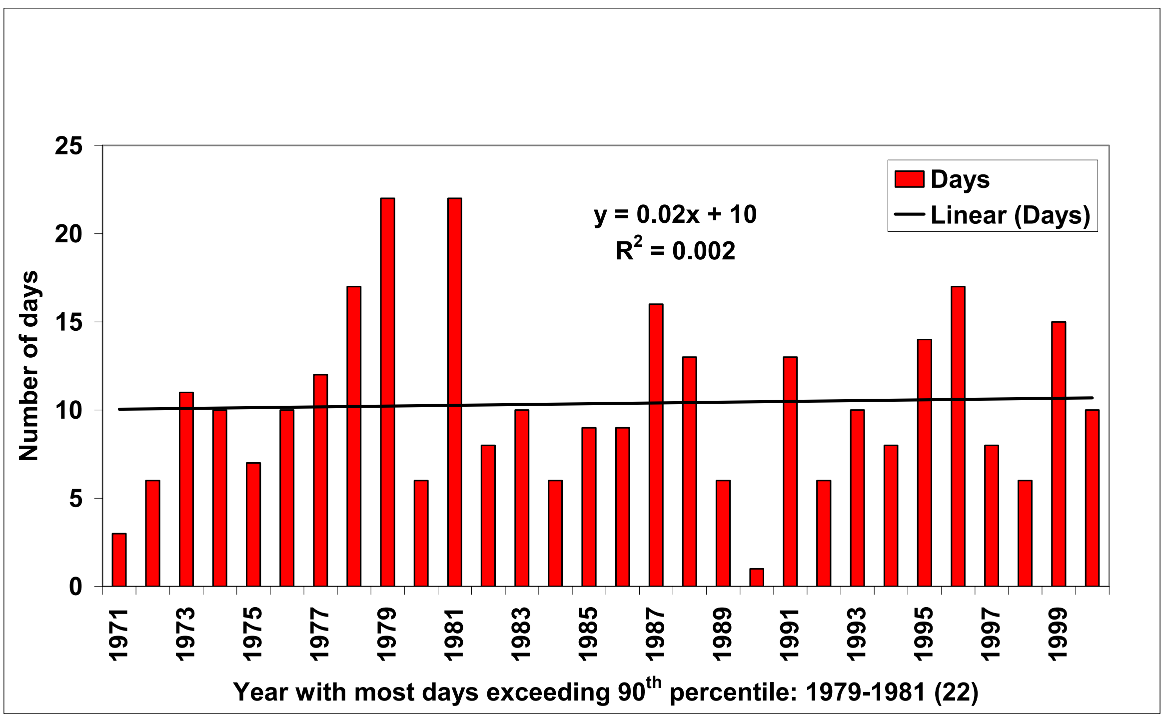


Figure 6.21: Counts of days each year, 1971-2000, in Gassim with thresholds above the 90th percentile of the winter (DJF) minimum daily temperature.

6.7.1.4 Tmax: Seasonal Analysis for Summer

The increase in Tmax in recent decades (Figure 6.17) has been accompanied by a decrease in the number of day thresholds below the 10th percentile (38.5°C), and by a marked increase in the number of day thresholds above the 90th percentile (44.6°C) of the daily Tmax in summer (Figures 6.22 and 6.23, respectively). This is apparent since about 1995 with a trend of an extra 1.6 days per year.1976 has the highest number of days below the 10th percentile value (28 days) while 2000 has the highest number above the 90th percentile (58 days).

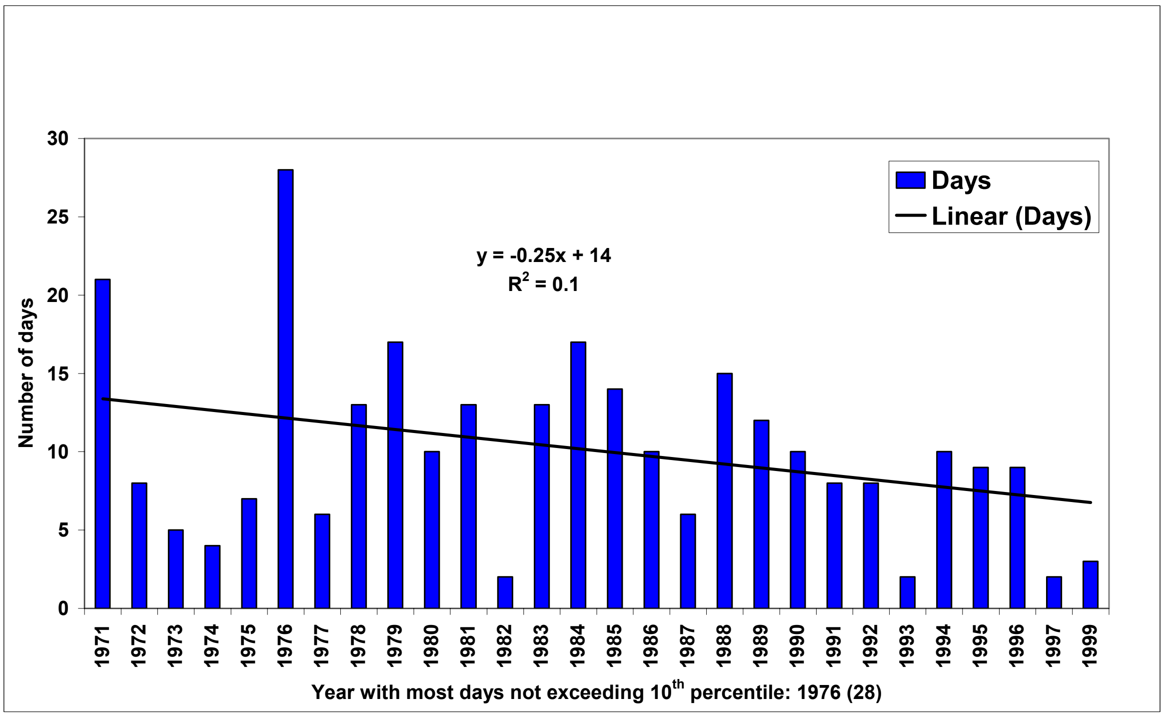


Figure 6.22: Counts of days each year, 1971-2000, in Gassim with thresholds below the 10th percentile of the summer (JJA) maximum daily temperature.

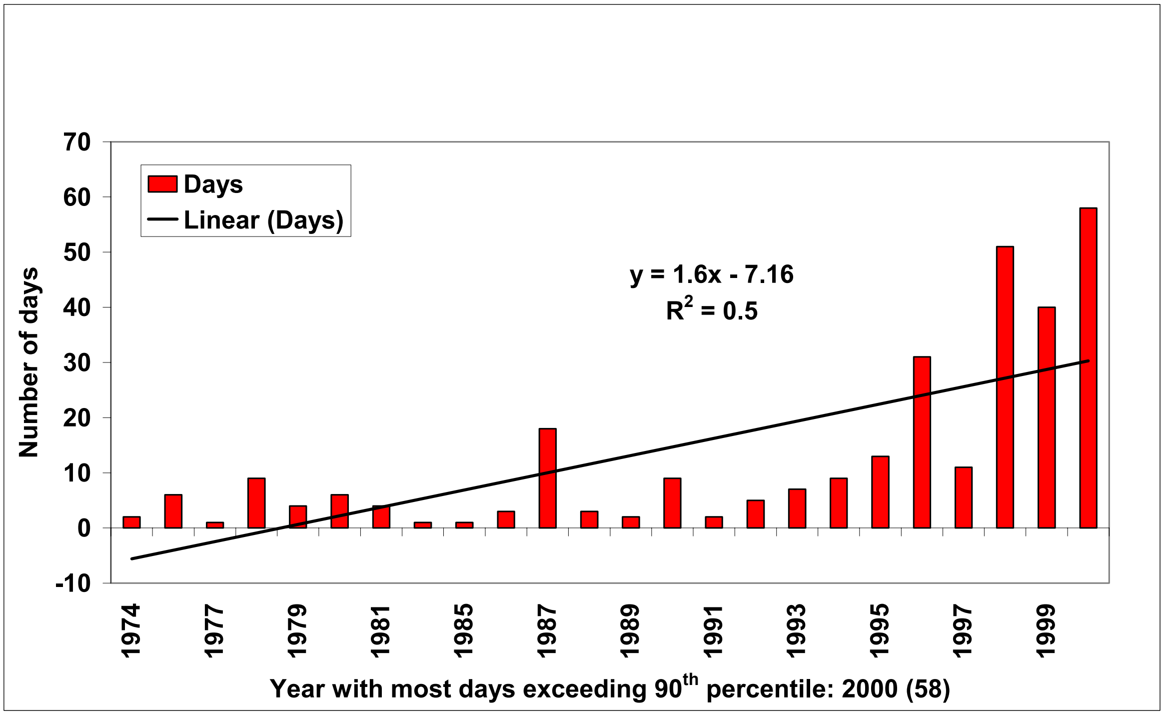


Figure 6.23: Counts of days each year, 1971-2000, in Gassim with thresholds above the 90th percentile of the summer (JJA) maximum daily temperature.

6.7.1.5 Tmin: Seasonal Analysis for Summer

Figure 6.24 shows a negative trend in the number of days exceeding the 10th percentile (21°C) and that 1976 has the highest number of days below the 10th percentile value (19 days). Figure 6.25 reveals a positive trend in the exceedence of the 90th percentile (27°C) and that 1998 has the highest number of days above the 90th percentile (35 days).

Figures 6.22 - 6.25 demonstrate an increasing number of days above the 90th percentile and a decreasing number below the 10th percentile of Tmax and Tmin. This provides a general picture of warming and an increased frequency of relatively extreme temperature events, which has taken place in the Gassim area, especially during the summer. The local effects on agriculture and the farmers' perceptions of these changes are discussed in Chapter 7.

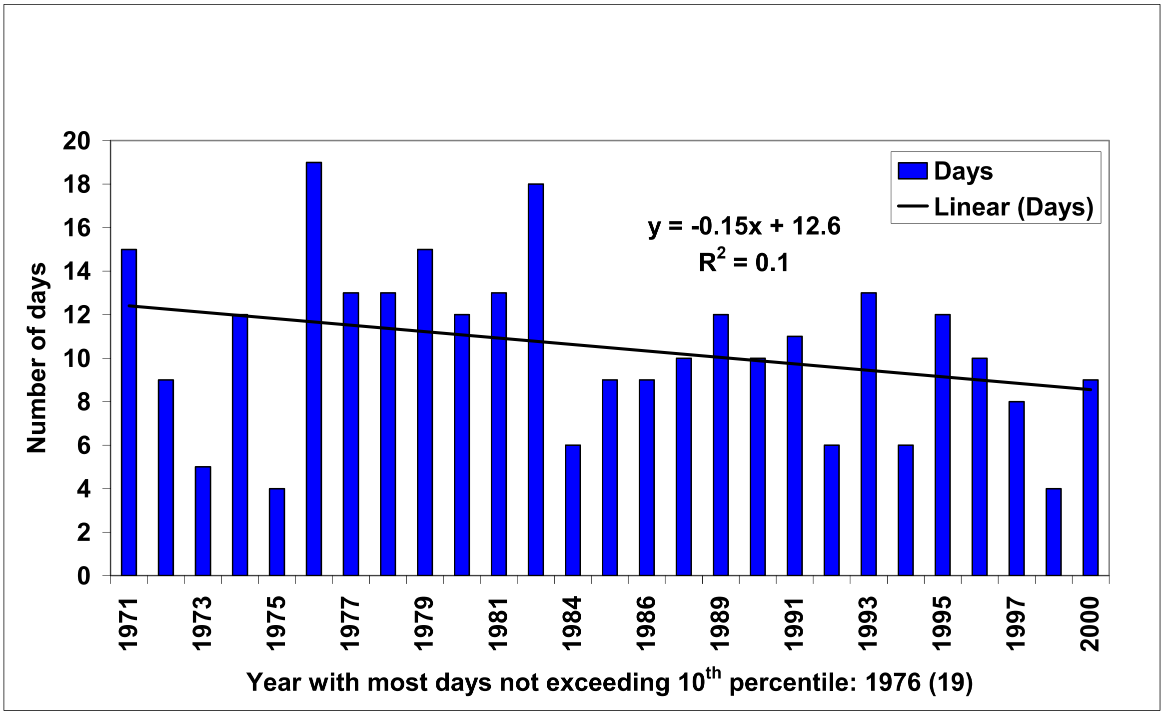


Figure 6.24: Counts of days each year, 1971-2000, in Gassim with thresholds below the 10th percentile of the summer (JJA) minimum daily temperature.

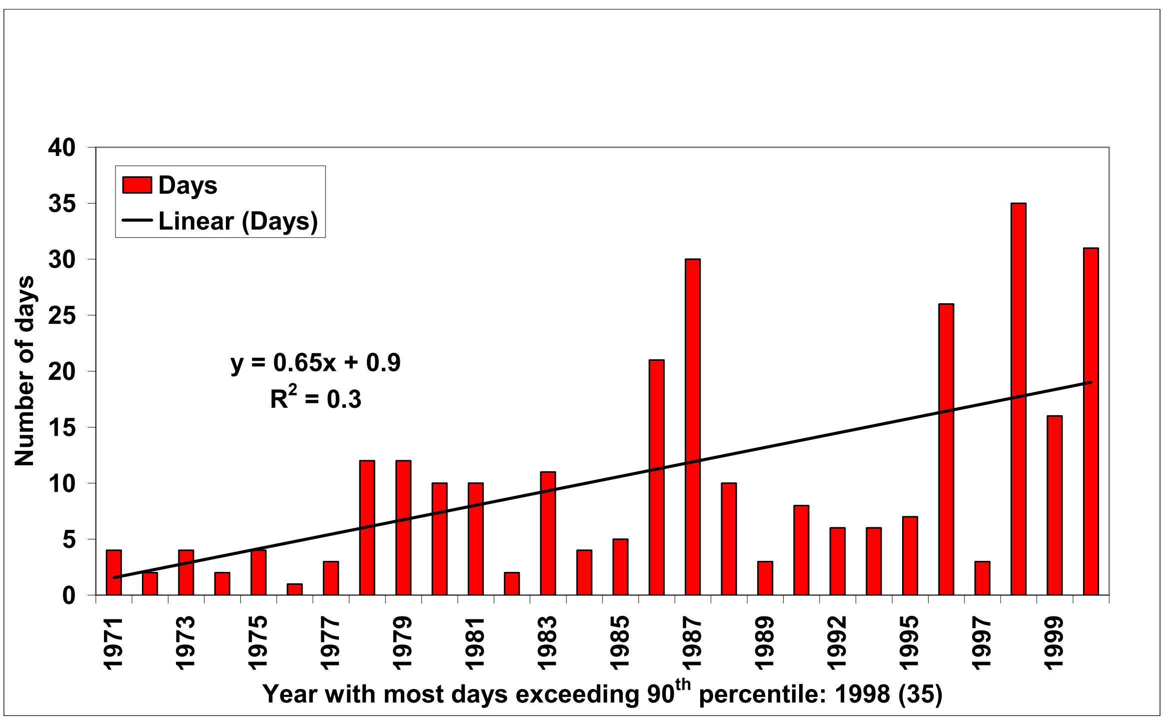


Figure 6.25: Counts of days each year, 1971-2000, in Gassim with thresholds above the 90th percentile of the summer (JJA) minimum daily temperature.

6.7.1.6 Statistical Significance of Liner Trend in Tmin and Tmax

The trends presented in Figures 6.18 – 6.25 were assessed for statistical significance by using a T-test to determine whether or not the average of the first 15 years of the series (1971-1985) count of days is significantly different from the average of the last 15 years (1986-2000). Table 6.5 shows that the number of days over 30 years (1971-2000) during the summer season (JJA) with percentile thresholds below a 10^{th} and above the 90^{th} of the daily Tmax do have a significant difference between the two averages. In addition, thresholds above the 90^{th} percentiles of the daily Tmin have a significant difference between the two averages in the same season. There are no other significant differences between the averages. This has pointed out that there is an increase of the frequency of extreme daily temperatures in the study area.

No. of days above/below threshold	**R^2**	**Trend days/year**	**Sig. level**	**Figure caption no**
>10^{th} Tmax (DJF)	0.07	y = -0.21x + 13	.540	6.18
<90^{th} Tmax (DJF)	0.01	y = 0.1x + 8.1	.478	6.19
>10^{th} Tmin (DJF)	0-00	y = -0.01x + 9.5	.593	6.20
<90^{th} Tmin (DJF)	0.00	y = 0.02x + 10	.804	6.21
>10^{th} Tmax (JJA)	0.1	y = -0.25x + 14	**.030**	6.22
<90^{th} Tmax (JJA)	0.5	y = 1.6x – 7.16	**.007**	6.23
>10^{th} Tmin (JJA)	0.1	y = -0.15x + 12.6	.109	6.24
<90^{th} Tmin (JJA)	0.3	y = 0.65x + 0.9	**.031**	6.25

Table 6.5: Analyses of trend significance in the number of extreme days over 30 years (1971-2000) during the summer and winter (percentile thresholds below the 10^{th} and above the 90^{th} percentile of the daily Tmax and Tmin). The number given in bold in the forth column are significant to at least 5%.

6.7.1.7 Analysis of Decade-mean Percentiles

The observed frequencies for extreme temperature events during the baseline period (1971-2000) are investigated using six indicators: 1^{st}, 5^{th}, 10^{th}, 90^{th}, 95^{th} and 99^{th} percentiles of Tmax and Tmin. The six indicators are based on observed daily data in order to understand changes in extremes and variability. Figure 6.26 depicts

the changes and the trends in Tmax divided into three decades. It can be noted that positive trends are evident in the 5th, 90th, 95th and 99th percentiles of the daily Tmax in each decade, while in the 10th percentiles there are no differences between the first two decades, whereas in the last decade Tmax increases. In terms of the 1st percentiles there are increases followed by decreases. In terms of Tmin, the 5th, 10th, 90th, 95th and 99th percentiles reveal a positive trend over the decades, while the 1st percentiles do not show any change.

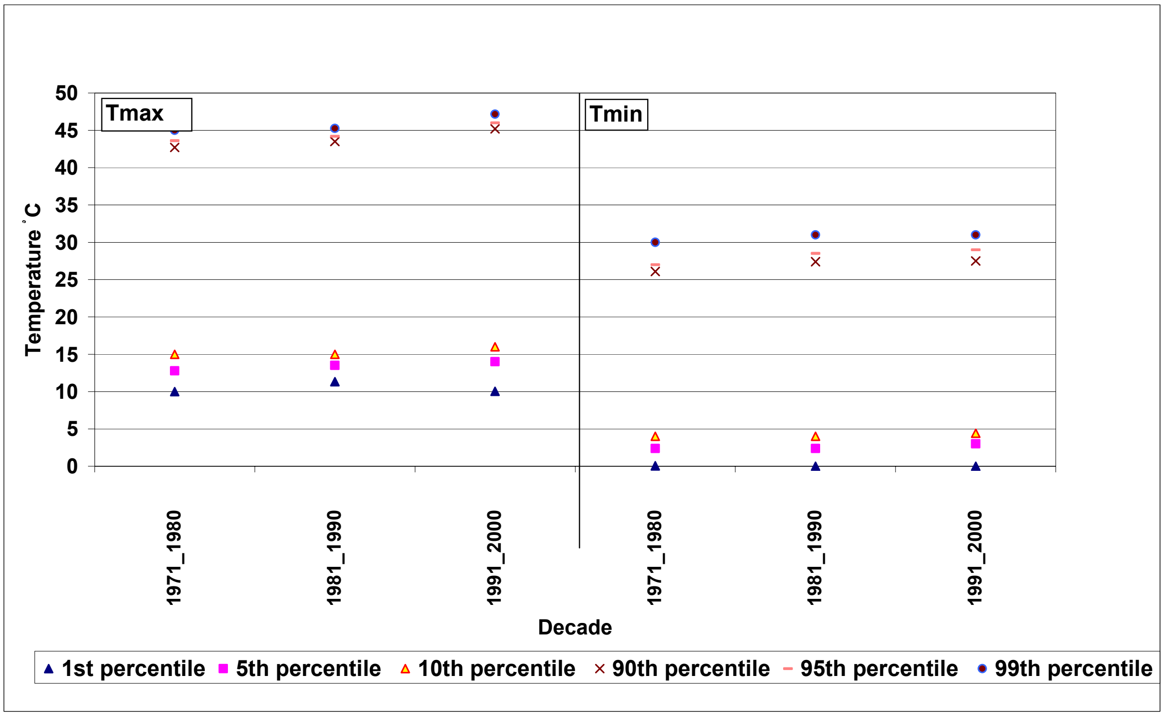


Figure 6.26: Percentiles of daily Tmax and Tmin during December - January and July - August, Gassim temperature record.

6.7.1.8 Frost Events

Figure 6.27 indicates that there has been no trend or significant change in the number of nights with frost (the number of nights with Tmin ≤ 0°C) in Gassim over the 30-year period.

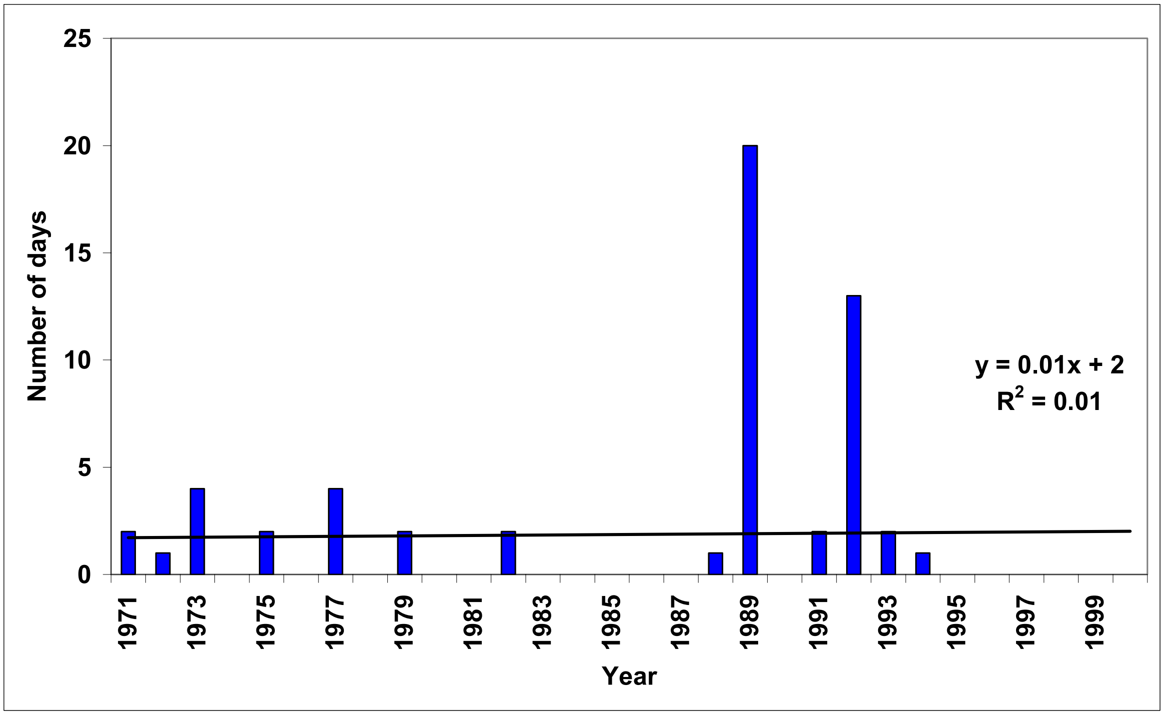


Figure 6.27: Total number of frosty nights per year (≤0°C) from 1971-2000 in Gassim.

6.7.2 GCM Simulation of Extremes in Daily Temperature

6.7.2.1 Tmax, Tmin and DTR

This analysis of current and future daily trends in Tmin and Tmax daily uses output from HadCM3 under the SRES A2 and B2 emissions scenarios. The dataset covers the two future periods (2010-2039 and 2070-2099) and is used to analyse the variability and trend of future daily temperature extremes.

Figure 6.28 shows the annual Tmax, Tmin, and DTR for the observations and HadCM3 simulation. Both Tmax and Tmin increase continuously during the 2020s and the 2080s, but the climate model predicts that there will be no significant trends or changes in the DTR under either scenario.

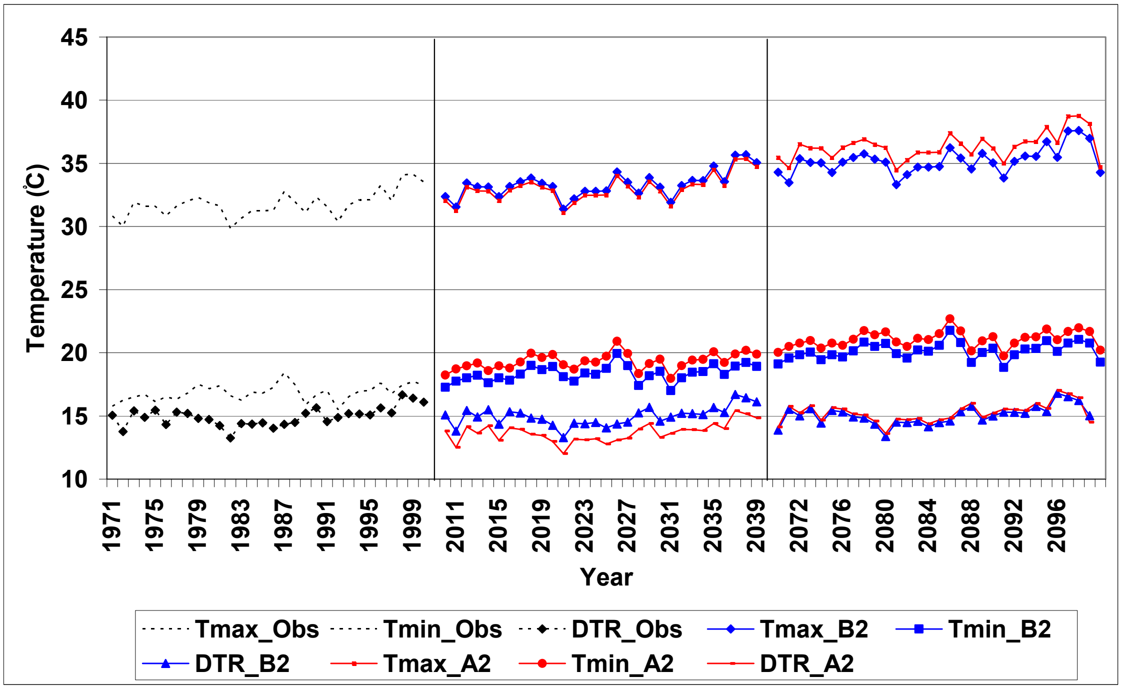


Figure 6.28: Observed and simulated Tmax and Tmin, and DTR (simulated by HadCM3 under scenarios A2 and B2). (Future periods show observed temperature plus the change in temperature for the period).

6.7.2.2 Percentile Analysis

The simulated frequencies for extreme temperature events in the 2020s and the 2080s under the SRES A2 and B2 emissions scenarios are investigated using the six indicators (1st, 5th, 10th, 90th, 95th and 99th percentiles) by HadCM3 on the baseline period 1971 to 2000. The six indicators are based on the daily data in order to understand changes in extremes and variability in the future, and are calculated for winter and summer.

Figures 6.29 and 6.30 summarize the changes and the trends in Tmax during the winter and summer thresholds under scenario A2 by the 2020s and the 2080s, divided into three decades. As expected, warming can be observed in the 5th, 10th, 90th, 95th and 99th percentiles of the daily Tmax in both seasons, and there is an

increase in temperature in both scenarios with scenario A2 slightly warmer than B2. In addition, the 1st percentile does not reveal much change between the decades in each 30-year period, but does so between the two.

The threshold 1st , 5th, 10th ,90th, 95th and 99th percentiles of Tmax for winter and summer increase by the 2020s by 1.2°C and 1.5°C, respectively, and by the 2080s by 4.6°C and 3.4°C, respectively.

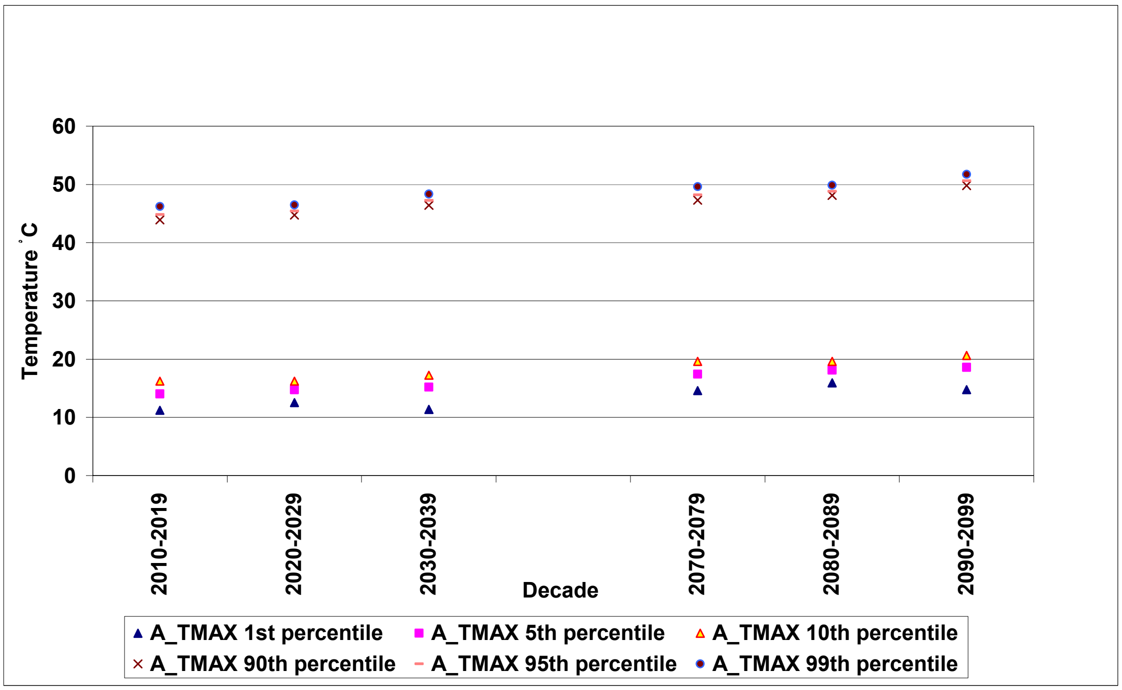


Figure 6.29: Percentiles of daily Tmax December - January and July - August, according to HadCM3 under scenario A2 in Gassim.

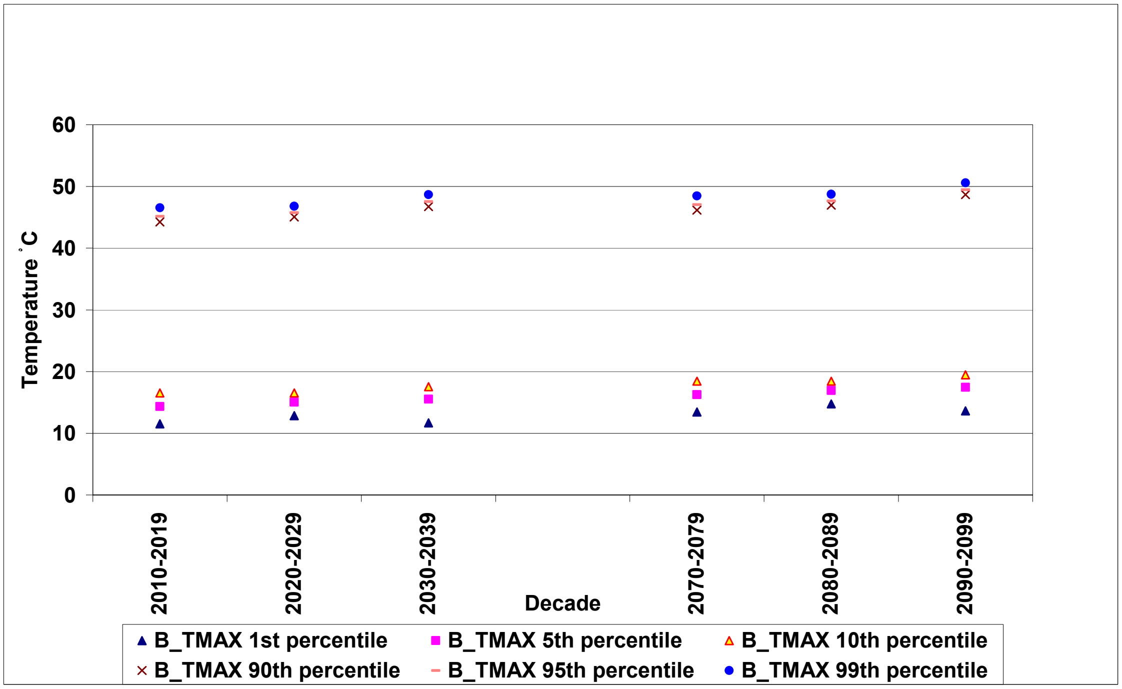


Figure 6.30: Percentiles of daily Tmax during December - January and July - August, according to HadCM3 under scenario B2 in Gassim.

Figures 6.31 and 6.32 display the results for Tmin with A2 and B2. The thresholds for all but the 1st percentile show increases under scenarios A2 and B2, by the 2020s and 2080s. The threshold for the 1st, 5th, 10th, 90th, 95th and 99th percentiles of Tmin for winter and summer all warm under scenarios A2 and B2 by the 2020s and will be warmer by about 2.5°C and 1.5°C, respectively, while by the 2080s it will be about 4.3°C and 3.3°C, respectively.

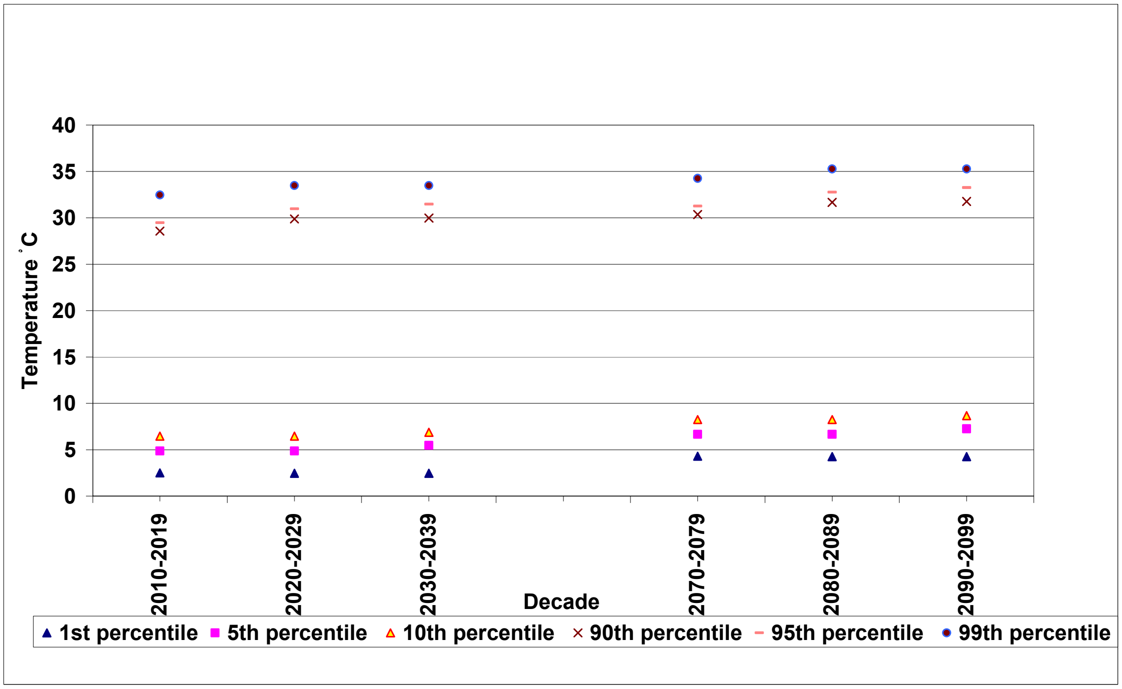


Figure 6.31: Percentiles of daily Tmin during December - January and July - August, according to HadCM3 under scenario A2 in Gassim.

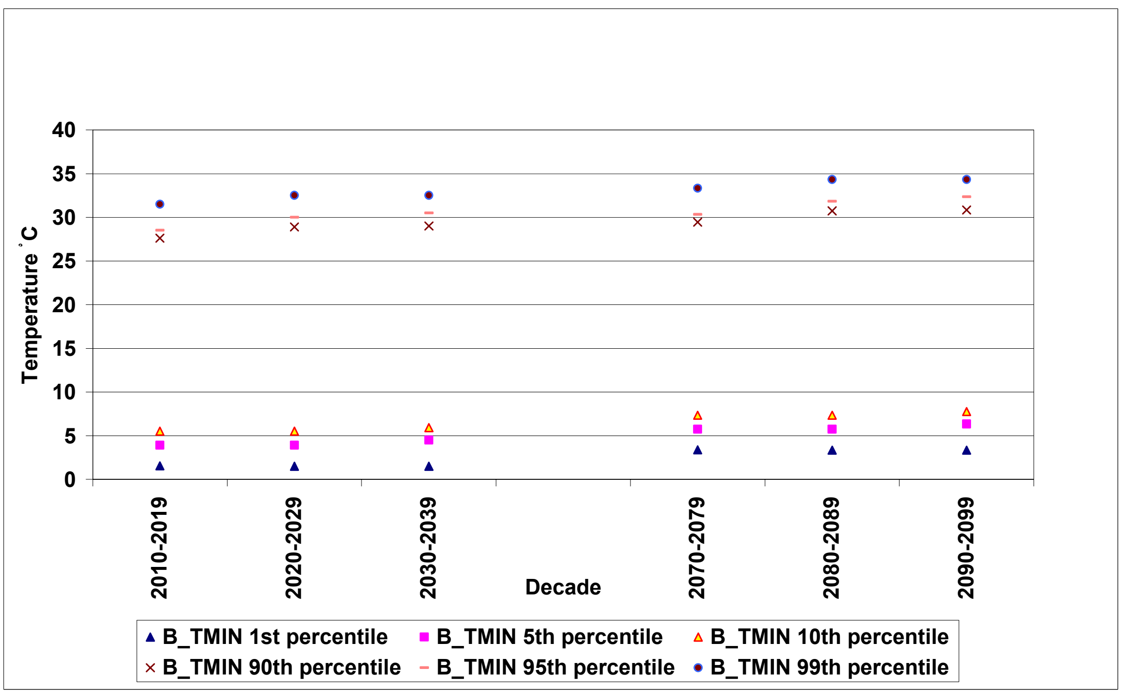


Figure 6.32: Percentiles of daily Tmin during December - January and July - August, according to HadCM3 under scenario B2 in Gassim.

6.8 Conclusions

The discussion of impacts and implications of these results appears in the following chapter. The objective of this chapter was to present and analyse climate change scenarios for Saudi Arabia in general and in more detail in Gassim.

The first part compared GCM simulations of current climate with the observed climate. At the scale of Saudi Arabia and in Gassim, the three GCMs generally reproduce the annual climate quite well (Tables 6.6 and 6.7).

GCM	Annual temperature	Rainfall	
		Annual	Wet season
HadCM3	Warmer (+3°C)	Good agreement	Too wet (50 mm)
CGCM2	Colder (-3°C)	Too wet (300 mm)	Too wet (300 mm)
ECHAM4	Colder (-3°C)	Dry	Good agreement

Table 6.6: Summary of GCM simulation of current climate in Saudi Arabia.

GCM	Annual temperature	Annual Rainfall
HadCM3	Colder (-0.5°C)	Too dry
CGCM2	Colder (-8.8°C)	Good agreement
ECHAM4	Colder (-0.4°C)	Too dry

Table 6.7: Summary of GCM simulation of current climate in Gassim area.

Climate scenarios from the three models were presented for Saudi Arabia. This is the first attempt for this region to use these models (and two emissions scenarios) to present future changes in temperature and rainfall. The GCMs produce increases in average annual temperatures over Saudi Arabia; by the 2020s, by 0.4° to 1.6°C, and by the 2080s by 2° to 4.8°C. In terms of annual rainfall, the patterns of change present no clear trends over either future period (spatially or temporally). Overall,

the changes range between -20 and 30 mm/year, relative to the control period of 1971-2000.

The results for Gassim are 0.99°C and 1.54°C warmer by the 2020s, and by the 2080s 3.15°C and 4.89°C warmer. In terms of rainfall for Saudi Arabia, and therefore for Gassim, there is some discrepancy between the models, e.g. HadCM3 produces a little decrease in each period ranging between -1 and -14 mm/year, whereas CGCM2 produces a little increase i.e. scenario A2 by 21 mm/year by the 2020s and 12 mm/year by 2080s. ECHAM4, produces increases in rainfall in both periods and with both emissions scenarios, larger than does CGCM2.

Changes in humidity are more consistent between the GCMs but are very small; by the 2020s from +1% to -1% and by the 2080s from +6% to -3%. Finally, for wind speed, there is disagreement between the small changes produced by the GCMs, which ranges between –0.12 and 0.12 m/s.

The fourth part of the chapter presented an examination of daily Tmax and Tmin for Gassim. The observed records exhibited an increase in temperature slightly faster for daily Tmax (0.7°C/decade) than Tmin (0.3°C/decade); this has caused an increase in the DTR (0.4°C/decade). These results differ from the IPCC (2001a) findings which concluded that in recent decades warming has involved a faster rise in daily Tmin than Tmax in many continental regions. This has resulted in a decrease in the DTR in many parts of the world.

Percentile analyses of daily Tmax and Tmin (winter and summer using five indicators) showed that the number of very warm days and nights is increasing, while the number of very cool days and nights is decreasing. The T-test of records indicated that there is no significant difference between the averages of two 15 year periods (1971-1985 and 1986-2000) for counts of days with percentile thresholds below the 10^{th} and above the 90^{th} of the daily Tmax and Tmin during winter and summer. Significant differences occurred with the number of days during the

summer season with percentile thresholds below the 10^{th} and above the 90^{th} percentile of the daily Tmax, (and also the 90^{th} percentiles of Tmin). The results suggest a general picture of warming and of an increase in the frequency of relatively extreme temperature events (e.g. over 0.5°C) in Gassim during the last 30 years.

Analysis of HadCM3 simulation reveals that the annual Tmax and Tmin continue to increase during the 2020s and the 2080s relative to the 1990s. According to the percentile analysis, the rise in Tmax and Tmin in the future climate during summer is principally associated with a reduction in the frequency of very cold days.

Finally, it should be taken in account that the outputs of the climate models are in no way to be considered as final predictions of the future climate as they are inherently uncertain. This issue is discussed further in Section 7.8. This chapter has now identified the potential for climate change in the study area and its impact on key weather indicators. The following chapter discusses the ramifications of such changes for irrigation in the study area, specifically its effects on ET_O, CWR, and LWGS, and includes a wider discussion of the implications for water management.

Chapter Seven: The Implications of Climate Change for Irrigation Water Use in Gassim

7.1 Introduction

The consequences of changes in climate variables such as temperature, rainfall, relative humidity, wind speed, and solar radiation will have a direct bearing on ET_O and CWR and irrigation is therefore widely held to be sensitive to climate change. Although on a global level, the IPCC (2001c) has indicated that climate change is unlikely to have a substantial impact on industrial and municipal demand for water but other studies show that it may substantially increase the demand for water for irrigation (e.g. for the UK by Downing et al., 2003). Chapter 6 explained how the climate may change in the study area, and noted, for example, that the observed temperature record presents a general picture of warming in the Gassim area of approximately 1.5°C over the last 30 years. The projections for future warming from three GCMs are 1.3°C by the 2020s and 4.1°C by the 2080s. Consequently, climate change could have significant negative ramifications for ET_O and CWR depending upon changes in the other climate influences which, all other things being equal, will lead to an increase in demand for groundwater for irrigation purposes.

Trends in future agricultural irrigation in the Gassim region will be predicated only in part on changes in climate, as areas such as Gassim are particularly vulnerable to other environmental factors such as dessication, salinization, desertification and land degradation. These processes may be exacerbated by climate change. For example, Utseta et al. (2001) pointed out that global warming may significantly increase the evaporative demand of crops, and therefore CWR will increase, resulting in higher water-tables which may increase soil salinity if the leaching fraction remains unchanged.

The need for studies into the demand for and use of irrigation water in the Gassim area is clear; as there is no doubt that one of the greatest challenges for the study area will be to balance the competing demands of water for irrigation and other sectors against a long term decline in groundwater levels plus the possibility of increased demand due to climate change. Under the current climate, increasing amounts of water are withdrawn from the only source available; aquifers and yet it is this source which is needed for future use. Saudi Arabia appears to be particularly vulnerable to climate change because of its high dependence on limited groundwater supplies as its primary water source.

In this regard, Chapter 7 describes the implications of climate change scenarios for ET_O, CWR, and LWGS in the Gassim area. Although the analysis examines winter wheat, as a typical crop, the methods are more generally applicable to other crops and locations in Saudi Arabia, and elsewhere. The first part of the chapter describes the methodology and presents the baseline data, before presenting a sensitivity analysis for the four meteorological variables used to estimate ET_O (based on Penman-Monteith). This is followed by a discussion of the impacts of climate change on ET_O, then on CWR, and finally on the LWGS. The final part of the analysis presents the results from discussions with farmers about climate related problems and adaptation strategies in the face of climate change. This is followed by a clarification of some of the key sources of uncertainty in the climate change scenarios, and the main conclusions.

7.2 Data and Methodology for Estimating Future ET_O

In Chapter 5, ET_O and CWR were estimated for the current baseline (1976-2000) climate, utilizing a monthly series based on the FAO's Penman-Monteith equation (Allen et al., 1998, see Section 5.7). For estimating future ET_O and CWR, this study uses two methods: the first one uses only future temperature data from

GCMs (HadCM3, CGCM2, and ECHAM4) for the two emissions scenarios and the two time horizons. This approach does not include any change in relative humidity, wind speed, and sunshine duration because:

- Temperature change is the main climate factor likely to change in future.
- The DDC website does not include sunshine duration (or other alternatives such as cloud cover) for all three GCMs.
- There is much greater uncertainty in GCM output of wind speed, cloud cover and relative humidity.

The second method uses wind speed and relative humidity from HadCM3 and sunshine duration was converted from cloud cover data which is provided by HadCM3. HadCM3 is the only model that offers sunshine data, albeit indirectly and therefore is the only model employed in this second method. The conversion of HadCM3 cloud cover to sunshine hours was based on the observed relationship between cloudiness and sunshine duration for Gassim. The regression equation calculated from observations (R^2= 0.35, Figure 7.1) used the following formula:

$$\text{Sunshine} = -0.6488 \text{ Cloud cover} + 8.03 \text{ (hours)} \quad (7.1)$$

This assumes that the observed relationship between cloud cover and sunshine duration holds in the future. Similar approaches have been used by Ghosh et al. (2003) and REIN (2004).

In addition, daily maximum temperatures from HadCM3 were used to investigate the sensitivity of the LWGS to changes in climate. The LWGS in the study area is about 130 days, and the period in which wheat can grow is from November to May (seven months). In very hot areas such as Gassim, wheat grows under its maximum temperature tolerance limits of 30° - 32°C (Moses, 1983). Therefore Tmax is an important parameter and increases in extremes during the LWGS could have negative effects on yield (see Section 7.7). This study selected 30°C as a maximum value during the LWGS.

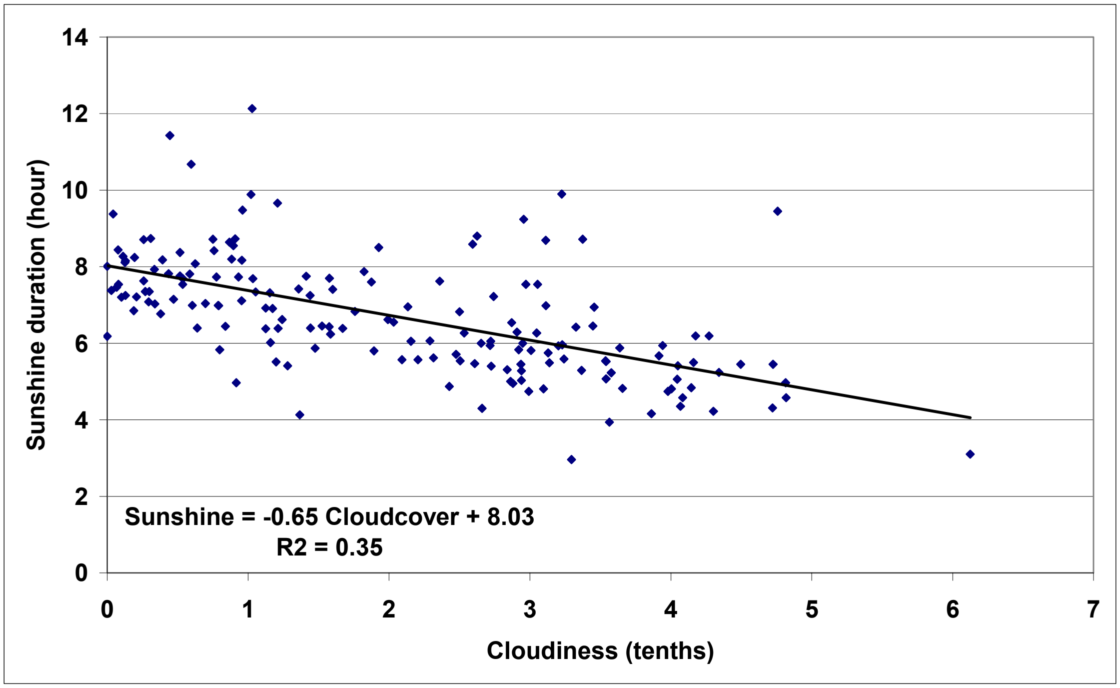
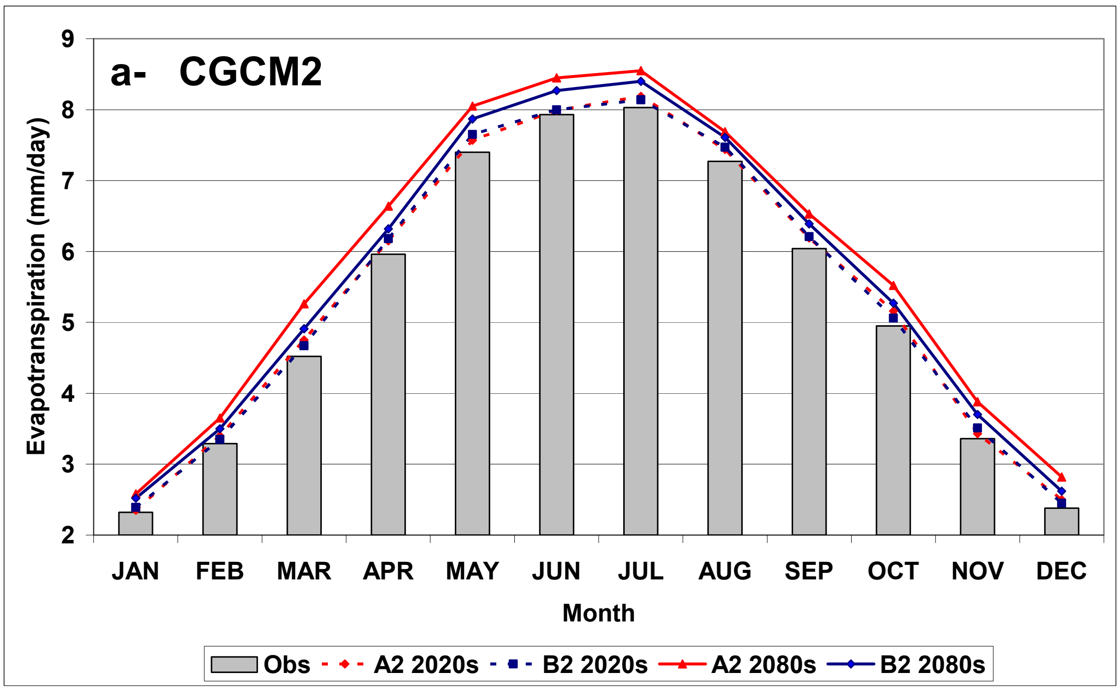


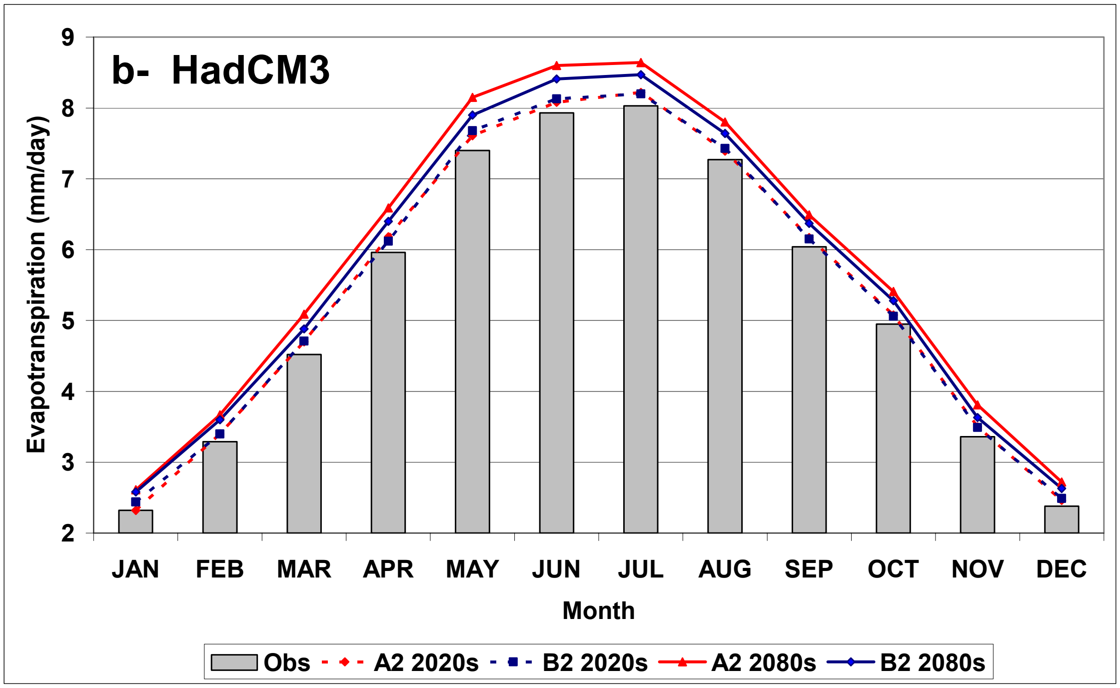
Figure 7.1: Relationship between observed cloudiness (in tenths) and sunshine duration in Gassim from 1985-1998.

7.3 The Impacts of Climate Change on ET_O

According to the first method, in which only temperatures were changed to estimate future ET_O, Figure 7.2 a-c shows the results expressed in mm/day. By the 2020s the monthly values of ET_O increase slightly in all cases. The differences in the annual averages of ET_O between the observed value (5.3 mm/day) and the model simulation average values (5.4 mm/day) are very small, and are almost indistinguishable by the 2020s. There are only very slight differences between the models and the emissions scenarios. By the 2080s, the annual average ET_O is higher in all cases by about 0.3 to 0.5 mm/day. The differences between the three models are indistinguishable whereas A2 is higher than B2, due to its higher temperatures. To summarise, a 1.3°C rise in temperature by the 2020s increases

ET_O by about 3%, and a 4.1°C rise in temperature by the 2080s increases ET_O by 12% under scenario A2, and 9% under scenario B2. Higher temperatures result in an increase in potential ET_O, largely because the water-holding capacity of air increases. These changes, although quite small, might well be accompanied by increased actual ET_O (depending on other influences) and therefore loss in soil moisture, requiring greater amounts of irrigation water.





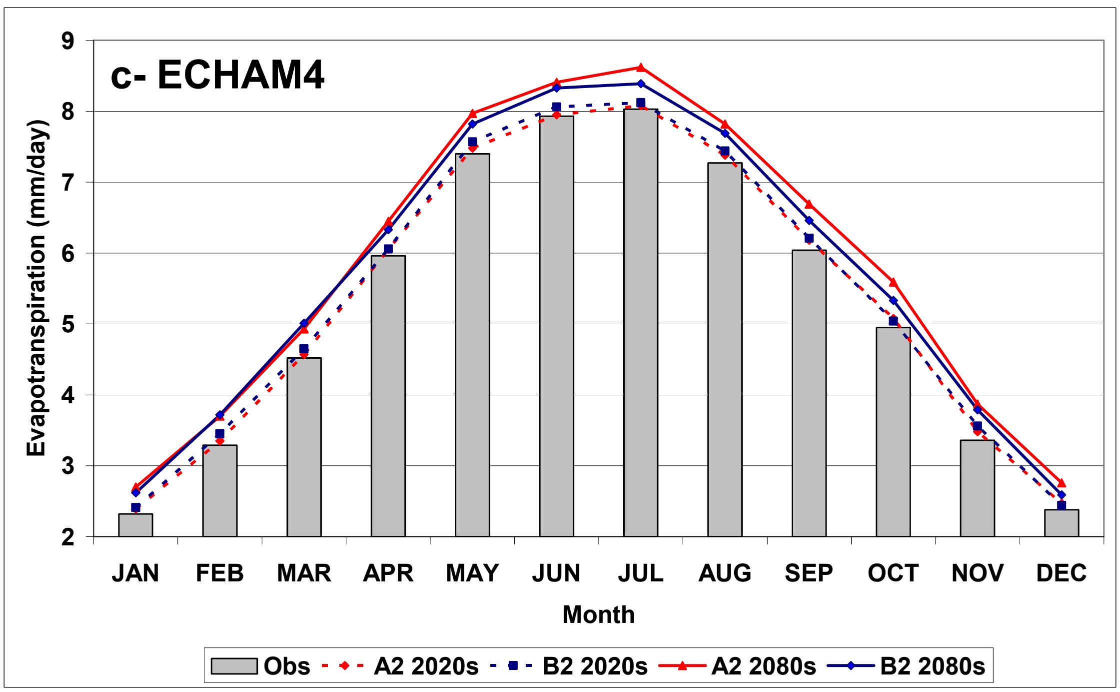


Figure 7.2: a-c: Comparison of average monthly ET_o (mm/day) for the baseline (present climate), and three models (a CGCM2, b HadCM3, and c ECHAM4) under scenarios A2 and B2, for the 2020s and the 2080s in the Gassim area.

Figure 7.3 shows a comparison between observed ET_O during the growing season with future ET_O scenarios. Observed ET_O is 887 mm/season, by the 2020s it ranges from 904 to 920 mm/season, and by the 2080s, it ranges from 954 to 999 mm/season. In the 2020s the highest values are produced by HadCM3 (B2), and the lowest by ECHAM4 (A2). By the 2080s the highest and lowest values are produced by CGCM2 (A2 and B2, respectively, see Figure 7.3).

It can be concluded that a 1.3°C rise in temperature by the 2020s increases ET_O during the growing season by about 2.8% on average, and a 4.1°C rise in temperature by the 2080s increases it by about 9.1% on average.

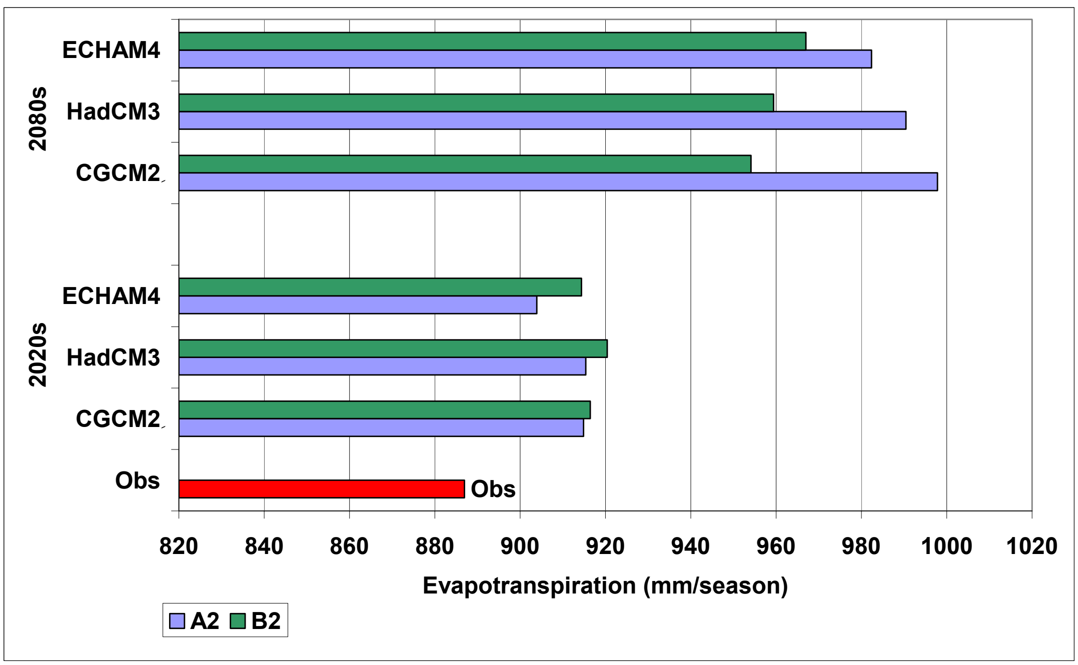


Figure 7.3: Seasonal (Nov-May) projected changes in ET_O by the three models under scenarios A2 and B2, compared with observed ET_O in the Gassim area, for the 2020s and the 2080s.

For the second method, which estimates ET_O for HadCM3 using all four variables, Figure 7.4 shows a comparison of results with the two methods. ET_O values are shown by columns representing the first method (temperature only), and by lines representing the second method (all four variables). The results reveal that in the annual averages there are no significant differences, but there are slight differences on the monthly scale, e.g. by the 2020s under both scenarios, the first method gives higher ET_O in the first half of the year, whereas the second method gives higher values in the second half of the year. By the 2080s, for the second method (A2) ET_O is higher in summer, but in general the differences are indistinguishable.

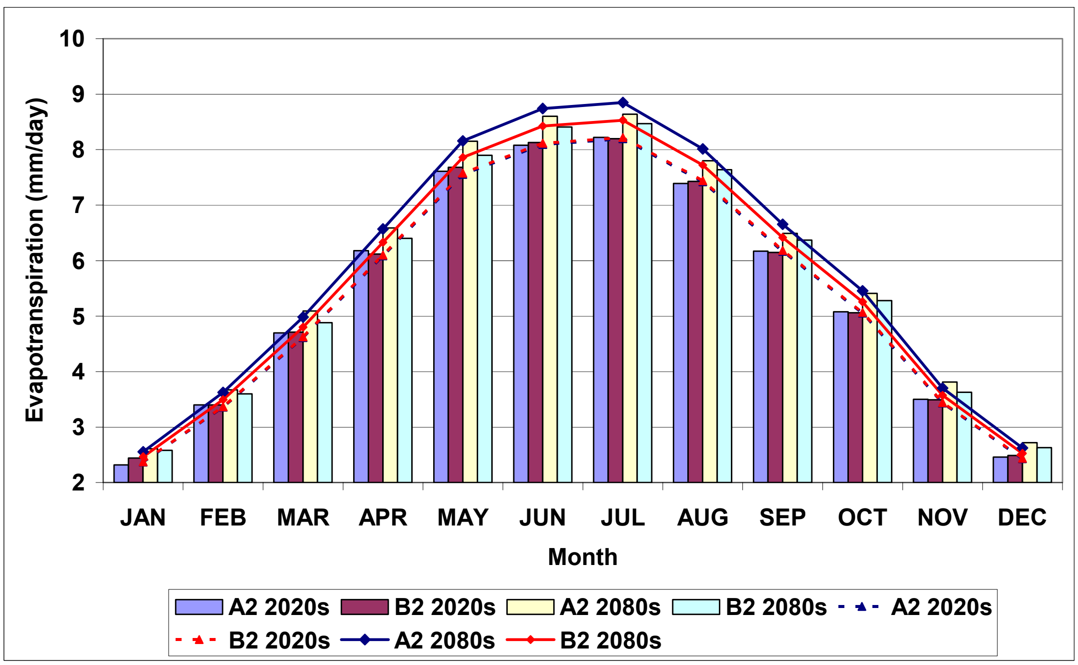


Figure 7.4: Comparison of average monthly ET_O (mm/day) between the two methods of estimation for HadCM3 under scenarios A2 and B2, for the 2020s and the 2080s in the Gassim area. (Columns= temperature only method, Lines= four variables method).

7.4 The Impacts of Climate Change on CWR

Figure 7.5 shows that the impact of climate change on CWR (following the method described in Chapter 5) in Gassim by the 2020s is not significant relative to the baseline period (increases range between 7 and 13 mm/season) and that there is little difference between the two scenarios: on average 3 mm/season. By the 2080s, the changes in CWR are much higher, with the A2 scenario producing increases in CWR ranging from 40 to 46 mm/season, and B2 producing increases ranging from 27 to 37 mm/season. By the 2020s and 2080s, CGCM2 (B2) produces the highest CWR, (360 and 389 mm/season, respectively).

Finally, the study concludes that the impacts of climate change on CWR suggest an increase in estimated irrigation needs (according to FAO methodology) of 2% to 4% per season by the 2020s, and 8% to 12% per season by the 2080s (summarised in Table 7.1). In terms of calculating CWR by the second method under HadCM3, the analysis reveals no significant differences, with the second method producing slightly lower values relative to the baseline climate, at about 0.8 mm/season by the 2020s and 3 mm/season by the 2080s.

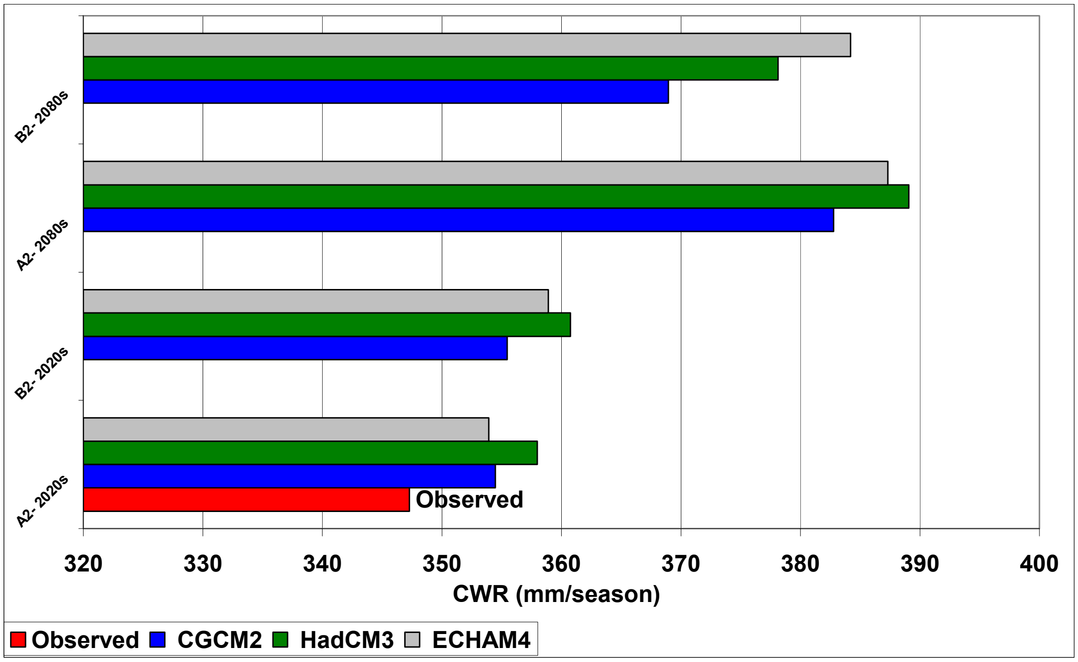


Figure 7.5: Projected changes in CWR (mm/season) for wheat in view of ET_o changes in the Gassim area.

Period	Climate change	
	A2	B2
The 2020s	3%	3%
The 2080s	12%	9.3%

Table 7.1: Impacts of climate change on CWR in the Gassim area for the three climate models, based on scenarios A2 and B2.

7.5 Sensitivity of ET_o to Variations in Input Variables

ET_o is the most important factor affecting CWR and is therefore an important consideration for the management of water resources in Saudi Arabia. Accordingly the aim of this section is to investigate the sensitivity of ET_o and hence CWR to

variations in input variables. The effect of climate change on ET_O depends on the characteristics of the site, the PE formulae used and, whether it uses more than one climatic input (Arnell, 1996). Average January and July reference values for ET_O were calculated using the Penman–Monteith method (Allen et al., 1998) and its sensitivity was explored by altering the individual climatic parameters, whilst keeping the other parameters constant. For example, ET_O sensitivity to temperature change was assessed by varying the temperature over a range of -3° to +3°C, and likewise for relative humidity, wind speed and sunshine.

Table 7.2 shows that ET_O, in terms of a mm response to per cent changes (or 1°C for temperature) in input variables, is most sensitive to temperature; a 1°C increase in temperature could result in an increase of 0.12 mm/day (0.14 mm/day) January (July). An increase in temperature as little as 1°C could result in an increase in CWR of about 103 m^3/ha/season for wheat in the study area. Also ET_O is quite sensitive to wind speed, a 1% increase in wind speed could result in an increase of 0.023 (0.018) mm/day January (July). ET_O is less sensitive to relative humidity; only decreasing by -0.004 mm/day against a 1% increase in humidity in January (-0.008 mm/day in July). These values are similar for sunshine (Figures 7.6 and 7.7). Temperature and wind speed therefore appear to have the major influence on ET_O values in the study area. In contrast, Penman-Monteith was found to be most sensitive to changes in temperature and net radiation and least sensitive to wind speed in Nebraska, Kansas and Tennessee, although the degree of sensitivity varied between the sites and from day to day (Arnell, 1996). Arnell (1996) also cited a sensitivity analysis using Penman-Monteith in Britain that showed a high sensitivity to changes in humidity in particular. Martin et al. (1989) in the mid-west of the USA, found the greatest sensitivity to changes in radiation. These contrasting examples, and the seasonal differences in sensitivity clearly demonstrate the influences of actual climatic values on the sensitivity of Penman-Monteith to given changes in their values (in percentage terms).

	January ET_O	July ET_O
Parameters	**Sensitivity**	**Sensitivity**
Temperature	ET_O = 0.12 mm per 1ºC change in Temperature	ET_O = 0.14 mm per 1ºC change in Temperature
Humidity	ET_O = -0.004 mm per 1% change in Humidity	ET_O = -0.008 mm per 1% change in Humidity
Wind Speed	ET_O = 0.023 mm per 1% change in Wind	ET_O = 0.018 mm per 1% change in Wind
Sunshine	ET_O = 0.006 mm per 1% change in Sunshine	ET_O = 0.012 mm per 1% change in Sunshine

Table 7.2: Estimated changes in ET_O values in response to changes in climatic parameters (temperature, relative humidity, wind speed and sunshine duration) during January and July.

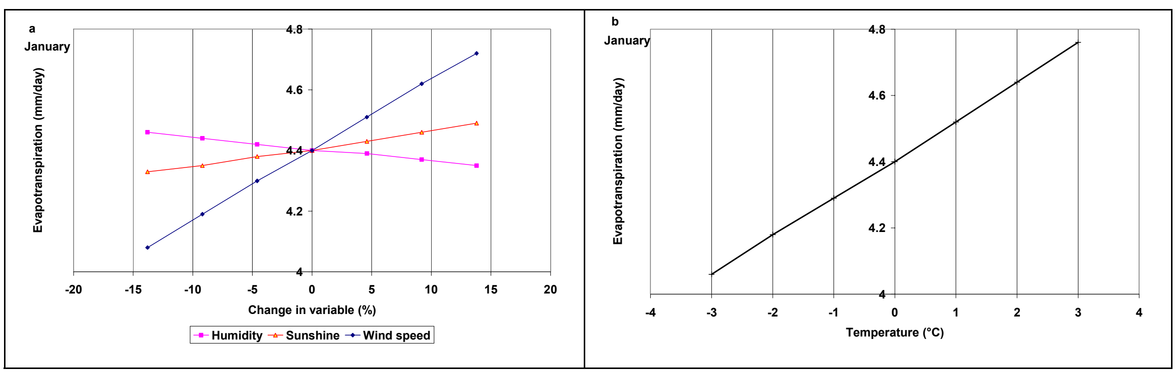


Figure 7.6: a,b: January ET_O changes in response to changes in climatic variables (temperature, relative humidity, wind speed and sunshine duration) in the Gassim area.

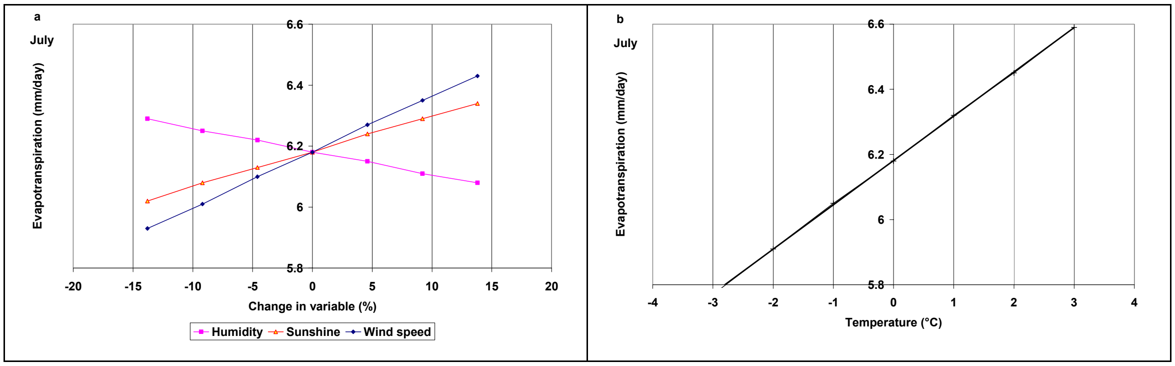


Figure 7.7: a,b: July ET_O changes in response to changes in climatic variables (temperature, relative humidity, wind speed and sunshine duration) in the Gassim area.

7.6 The Impacts of Climate Change on the Length of the Wheat Growing Season (LWGS)

Temperature is the main climate factor affecting the length of the agricultural season and this is especially so for wheat in Gassim as it grows close to its maximum temperature tolerance limits (given existing varieties). Hence, a strong warming trend in the region could seriously impact on the LWGS by shortening it, and extremely high temperatures could negatively affect yields. The results confirm that a decrease in the LWGS already occurred during 1970-2000 (Figure 7.8), based on an increase in the number of days above 30°C. The average LWGS is currently 152 days (theoretical growing season or continuous period of days ≤30°C) whilst under the modelled scenarios A2 and B2, it is 140 and 138 days, respectively, for the 2020s. By the 2080s, based on scenarios A2 and B2, it drops to about 107 and 120 days, respectively. Thus, the growing-season length decreases by 9% and 26%, relative to the baseline. It should be noted that the winter wheat grown by farmers in the Gassim area requires on average about 130 days to mature and therefore, and in the light of climate change, farmers will need

to adapt to a shorter growing season. Higher temperatures may also lead to a shortened actual growing season as the development of the wheat may occur at a faster rate.

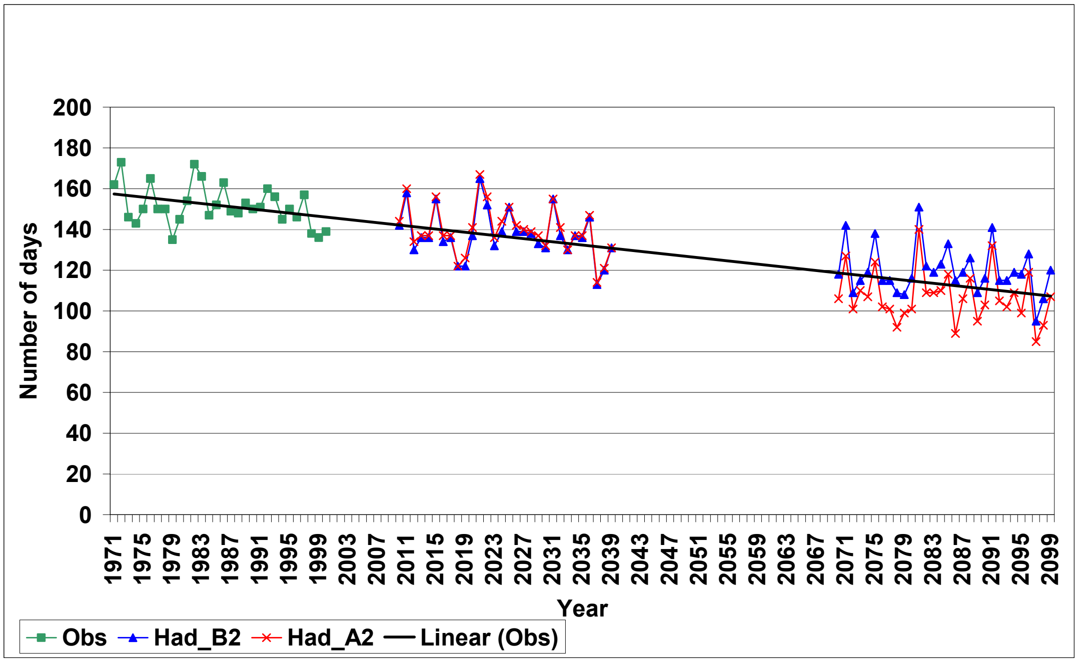


Figure 7.8: The observed total number of days ≤30°C during the growing season for wheat, compared with those projected by HadCM3, based on scenarios A2 and B2, in the Gassim area. (The linear trend line represents an extrapolation of the observed trend 1971-2000 for visual purposes only).

The rise in Tmax and Tmin in the future climate is principally associated with a reduction in the frequency of very cold days. These changes might have some affect on crop yield and water resources. Adams (1997) highlighted that various sectors of the agriculture community are affected by extreme heat, i.e. livestock, crops and water resources. The negative effects of extreme temperature and heat events on wheat are summarised in Section 2.3.6. Amir (2001) highlighted that heat stress is also a common constraint during anthesis and grain filling stages in many temperate environments in South and West Asia, including the study area. However, it should be noted that the next section will show that the farmers are

already growing wheat beyond the theoretical growing season, so an increase in extreme temperatures may not necessarily cause the farmers to stop growing wheat because they are currently not strongly concerned about the negative effects on yield or the amount of water they use.

7.7 A brief Analysis of Farmers' Perceptions and Attitudes towards Climate Change and Agriculture in Gassim

A questionnaire was undertaken in spring 2004 in order to examine the attitudes and behaviour of farmers in the study area towards the issue of climate and climate change in relation to their activities. The questionnaires were administered to the owners of the eight selected farms (six TFs and two CFs, see Section 1.4), and to six other farmers with experience in either TFs or CFs. In addition, the researcher met and discussed with officials in the appropriate branch of the MAW and academics at the Agricultural College in Gassim University. The questionnaires were conducted as face-to-face discussion in an open and cordial manner. The aim of the questionnaire and results are presented in the next section. The questions were structured around four themes: evidence for agricultural impacts from climate variability; other non-climate challenges to farming; What is the water use situation, and how important is climate change and what kinds of responses could be adopted?

1. **Evidence for agricultural impacts from climate variability.**

Question One: Are there any problems due to high/low temperatures?

Farmers are not concerned about minimum temperatures in the Gassim area because they are generally ideal for wheat. Most of the farmers also noted that the

frequency of frosty nights has reduced. The highest recorded temperatures occur only in the summer (e.g. 1998) and the farmers reported no problems as wheat is a winter crop, and the winter of 1998 (very warm year) was moderate. According to the record, the winters of 1979,1987,1994,1999 and 2000 were all warmer than 1998 in the study area. A few farmers (3) pointed out that sometimes high temperatures during the growing season can negatively affect the yield, especially if they occur at the end of the season. Maximum temperatures are sometimes considered dangerous for wheat, and therefore farmers, especially in the CFs, irrigate their wheat throughout the entire day (24 hours) in order to ameliorate against the effects of the high temperatures, not for irrigation but for cooling, and this is sometimes successful.

Question Two: Are there any problems due to changes in the length of the growing season?

The farmers reported no problems in this matter as the available time for growing wheat in Gassim is currently longer than that needed by the wheat crop. Wheat needs about 130 days on average, and the farmers' actual growing season is from the beginning of November to May (212 days) (see Section 7.6).

Question Three: Have the farmers or managers noted any changes in climate, and what have been the implications for yield?

Most farmers have noted that, in particular, minimum temperatures have increased and that winter has become warmer with fewer frosty nights. Moreover, they noted that high temperatures, and especially heat waves that occur during the growth cycle especially at the end of the growing season, which may put it under risk and affect yields (see Picture 7.1).

2. **What are the other (non-climate) challenges to farming?**

Question Four: What are the main constraints to agricultural practice in Gassim?

All wheat farmers questioned who grew wheat said that the main problem they face is with grass and weeds, and the cost of the herbicides which they need to suppress them, because their presence directly reduces production. The second most common complaint was the cost of electricity and fuel. Some mentioned the higher temperatures, and finally, the increasing salinity of their groundwater.

Picture 7.1: Wheat Crop affected by high temperatures in the CFs in the Gassim area, 2003.

3. **What is the current situation regarding agricultural water use in Gassim?**

Question Five: Is the water availability changing? (For example, changing groundwater levels or changes in the pricing of water)

All farmers noted that groundwater levels are declining dramatically and they know that abstractions exceed recharge (see Section 4.3.3). Many farmers have extended the pipes inside their wells in cases where water levels have declined. However, it should be noted that there is some small recharge of the aquifers where some of the water used in inefficient irrigation returns via percolation. In terms of water pricing, water for irrigation is still free of charge, and so farmers are not concerned about water use. However, the farmers (especially in the TFs) consider their costs for fuel and electricity to be high. It is note worthy that the

government recently separated the MAW and its responsibility for water into two ministries one for agriculture and another for water in order to improve water management across the agricultural, municipal and industrial sectors.

Question Six: Does the government (i.e. the MAW) provide support for changing the methods of water use?

Farmers said that some initiatives had been undertaken, such as providing loans to pay for modernizing irrigation methods in order to improve efficiency. In addition, the MAW distributes many leaflets and booklets as guides in water use, and organises courses and training in water use efficiency for farmers in the Gassim area. Every year there is a week called ‘’Tree Week’’, organised by the MAW over the whole country, which is aimed at educating the people in agricultural and water use matters, but the benefit is limited.

Question Seven: Do you have any incentives to reduce water use?

Answers were similar to Question Five. As water is free of charge, the farmers were generally not concerned about water use, so the only incentive to reduce it at present was the cost of the fuel used by the irrigation machinery.

The government owns the water resources in Saudi Arabia through the MAW which is the body responsible for the implementation of policy. In relation to its use in agricultural irrigation, according to the regulation of the MAW, each farm must have a license in order to have access to water, most of which is non-renewable (fossil) water.

4. **What is the importance of possible future climate change and what kinds of responses could be adopted?**

Question Eight: How would you (farmers/managers) respond to shorter growing seasons and / or more frequent extremes in temperature?

Although climate change may have an impact on the LWGS for wheat in the study area (see Section 7.6), farmers consider that the length of the growing season for wheat is not a major issue in the study area (see Question Two). In the case of more frequent extremes in temperature, farmers said they would increase crop irrigation in order to reduce the effects of high temperatures particularly in the CFs.

Question Nine: Do you think climate change will be a problem for your farming?

Owing to the fact that the study area already suffers from extreme temperatures, especially in summer, all the farmers were not very concerned about climate change, and for many of the farmers, climate change was not as big an issue as water availability and/or its efficient use. However, farming may well be affected by climate change because the climate does not only affect CWR or total yield, but also affects pests, diseases, flowering, ripening, germination etc. Climate also affects the timing of farming activities, such as land preparation etc.

These interview results provide a small sample, limited by time and resources, and therefore may draw only a partial picture of farming and opinions within the farming community in Gassim. Nevertheless, the findings are in general agreement with the opinions found in the academic community in Gassim University. These findings are discussed in relation to earlier sections on climate change impacts in the next section.

7.8 Responses to climate change: Adaptation Strategies for Irrigated Agriculture in Gassim

Despite Gassim's aridity, agriculture is the major sector of the area's economy but produces a high demand for water. De Pauw (2002) wrote that between 1980 and 1996, the area under irrigation more than doubled, aided by the use of modern irrigation technology, such as the centre-pivot. Figures 7.9 a-d show the expansion

of irrigation between 1983 and 1993, particularly in the centre of the Arabian Peninsula, which is represented by the Gassim area. In view of the fact that irrigation utilizes aquifers with fossil water, which are barely recharged, the area is threatened by water scarcity problems. In addition, future climate change in the study area suggests that these problems will be exacerbated to some extent.

Water and agricultural policies need to consider appropriate adaptation measures that might avoid the most severe consequences of climate change. In other words, policy should enable and support adaptation strategies for irrigation in its attempts to contend with extremes in the actual climate and as well climate change. But these efforts should be seen in the context of declining water availability and the need to develop sustainable water use which may require significant changes to current water supply policy and allocation. Changes in resource management need to enable adaptation to climate change, and also engender improvements in the irrigation systems in the study area, thereby promoting higher efficiency in current water use and improvements in economic productivity.

Adaptation has been defined by IPCC (2001c, p.982) as the

> *''Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities''.*

A range of measures exist that can be adopted to reduce the adverse impacts of climate change on irrigation. These measures ought to be considered as a first priority, and may be classified into short-term plans and long-term plans. Most can be considered 'no-regret' policies, i.e. ones that produce benefits regardless of climate change, especially where farmers may be using water inefficiently.

Short-term (1-5 year) plans may include:

- Modifying the irrigation applications e.g. irrigation applied at night or in the evening to reduce evaporation losses;
- Modifying the timing (interval between irrigations) to improve IS or the delivery of water and efficiency of water use (adopting more optimised scheduling see Section 5.13);
- Encouraging farmers to sow their wheat crops earlier in order to preserve water. Early sowing has an advantage in terms of FWUE (see Section 5.10), and early sowing avoids the excessive heat of mid-spring;
- Utilizing plastic pipes or cement canals instead of sand canals for irrigation (Picture 7.2);
- Changing surface irrigation methods into sprinkler irrigation could theoretically raise field application efficiency rates to 70%, especially in arid areas (Seckler et al., 1998). This study assumes existing efficiency rates of 55% for surface irrigation and 70% for sprinkler irrigation;
- Improving farmer's knowledge of crop water needs.

Long-term (5-10 year) plans can be divided into four types of response:

➢ **Policies and Institutions**

- Giving subsidies to farmers for changing from traditional methods of irrigation into modern through the MAW;
- Strategic planning for sustainable water use;
- Government licenses for digging wells with high criteria to protect groundwater;
- Public investment and financing of irrigation and water supply.
- Reviewing the whole agricultural policy for subsidies that encourage such high rates of water use – this is discussed in Chapter 8.

➢ **Economic Approaches**

- Water pricing is an important issue, and selling irrigation water instead of providing it free of charge could significantly cut waste. Water pricing and

market mechanisms could deliver efficiencies in water use relatively quickly. Al-Naeem (1999) computed that the cost of water for irrigation per cubic metre is about SR 0.23 ($ 0.06). Such low costs encourage farmers to use water inefficiency. However, the water authority may face complaints and opposition from farmers: my observations in the field and local newspaper reports suggest that there are already problems with recent increases introduced for fuel and there have been protests against the government over the cost of fuel and electricity (both important costs in abstracting deep groundwater). However, it is in the national interest to persevere with this strategy;

- Imported wheat would be much cheaper and more advantageous as the production of winter wheat is relatively inefficient and depletes scarce water resources. For example, economically, the harvest of 1991/92 was estimated to have cost the government about $ 480/ton, whereas world prices for wheat were only $ 100/ton (FAO, 1997) (see Section 1.4.1). This relates to ideas about 'virtual water' see for example Allan (2004).

➢ **Education/Awareness**

- Improve information systems about agriculture and irrigation for farmers, e.g. by the media and the internet;
- Improve and support research programmes on assessments of climate change impacts; currently there is no effort in this direction;
- Educate farmers on modern irrigation techniques in order to raise production and reduce water demand through (perhaps compulsory) courses;
- Train and support farmers in the study area on adaptation techniques;
- Support agricultural education within the education system and instigate training programmes for farmers (and trainees) to enhance their awareness of the issues.

- **Technical Approaches**

- Change crop patterns in order to support water conservation;
- Explore the potential for new water storage facilities and techniques;
- Government should invest in the development of new varieties and crops that need less water;
- Modernise irrigation methods e.g. application of modern sprinkler irrigation techniques to improve efficiency;
- Use flow meters on each well;
- Controlled well drilling;
- Discontinue the use of highly saline water for irrigation in order to conserve the soil and improve crop productivity.

These types of adaptation strategies are or will become increasingly important in reducing the impacts of climate change. Taking these adaptation strategies into account will also of course improve water use in irrigation and conserve water. This is true regardless of climate change, and can be considered typical ‘no-regrets’ type responses.

Picture 7.2: Example of unlined sand canals and cement canals in the Gassim area.

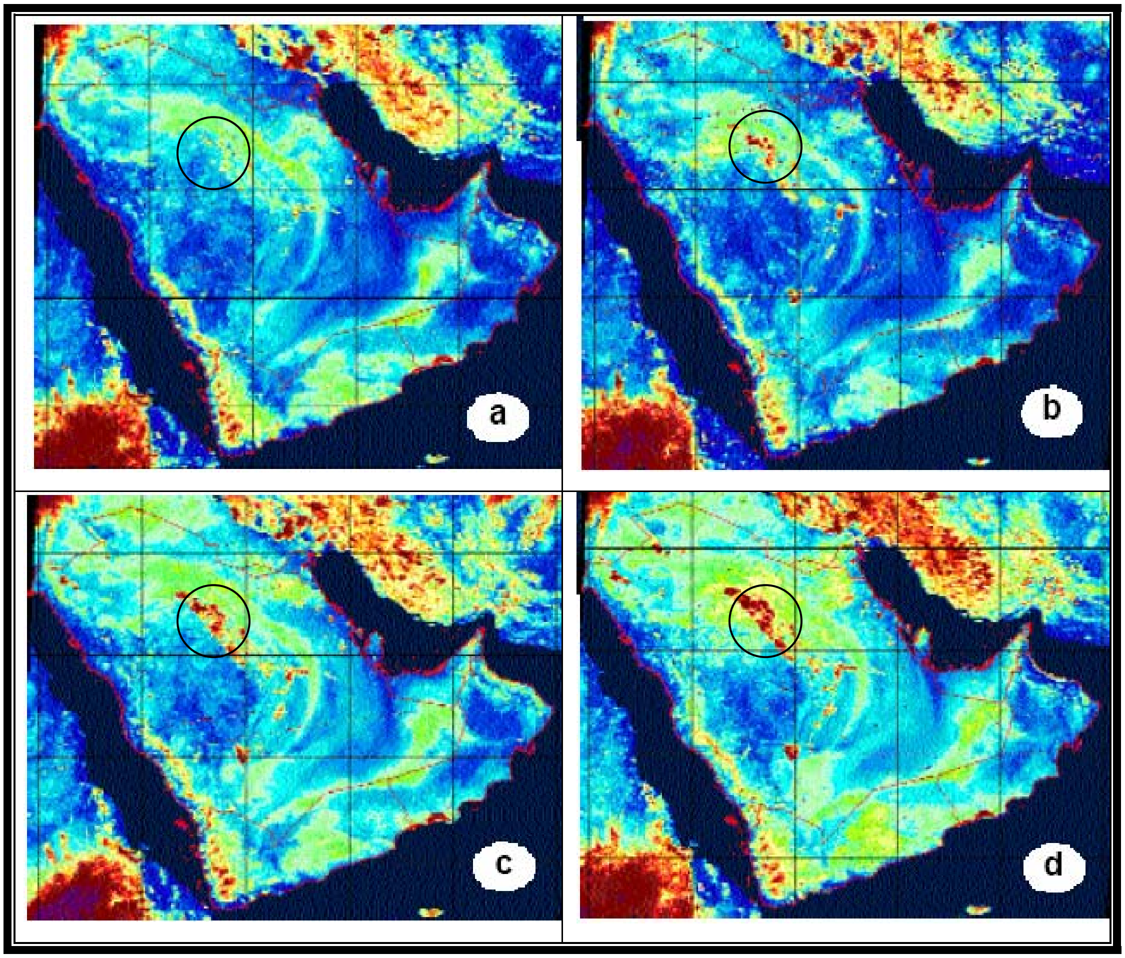


Figure 7.9: a-d: The circles highlight the Gassim area and the red patches reflect the expansion of irrigation, from AVHRR imagery. Situation in 1983 (a), 1986 (b), 1990 (c) and 1993 (d) (Source: De Pauw, 2002).

7.9 Discussion and Conclusions

7.9.1 Uncertainties about Scenarios of Future Climate Change and Climate Change Impacts

There are many uncertainties associated with using the results of GCMs for assessing future climate change impacts. There is great uncertainty about the

future rate of emissions of GHGs and their atmospheric concentration. Downing et al. (2003) stated that the main uncertainty lies within the amount of GHGs and aerosol that will be emitted, and Hulme et al. (2002, p.81) clarified that:

> *''Uncertainty about future emissions arises because we do not know with any confidence how populations, economies, energy technologies, and other social factors that influence greenhouse gas emissions will change in the future''*

Figure 7.10 shows the range of the global average temperature projections for six SRES scenarios using a simple climate model. This study used three GCMs (HadCM3, CGCM2, and ECHAM4) with two emissions scenarios based on A2 (high) and B2 (lower) generated by the IPCC SRES A2 and B2. These scenarios represent a good range of outcomes in both temperature and rainfall and therefore can be considered a reasonable guide to the range of outcomes for the area.

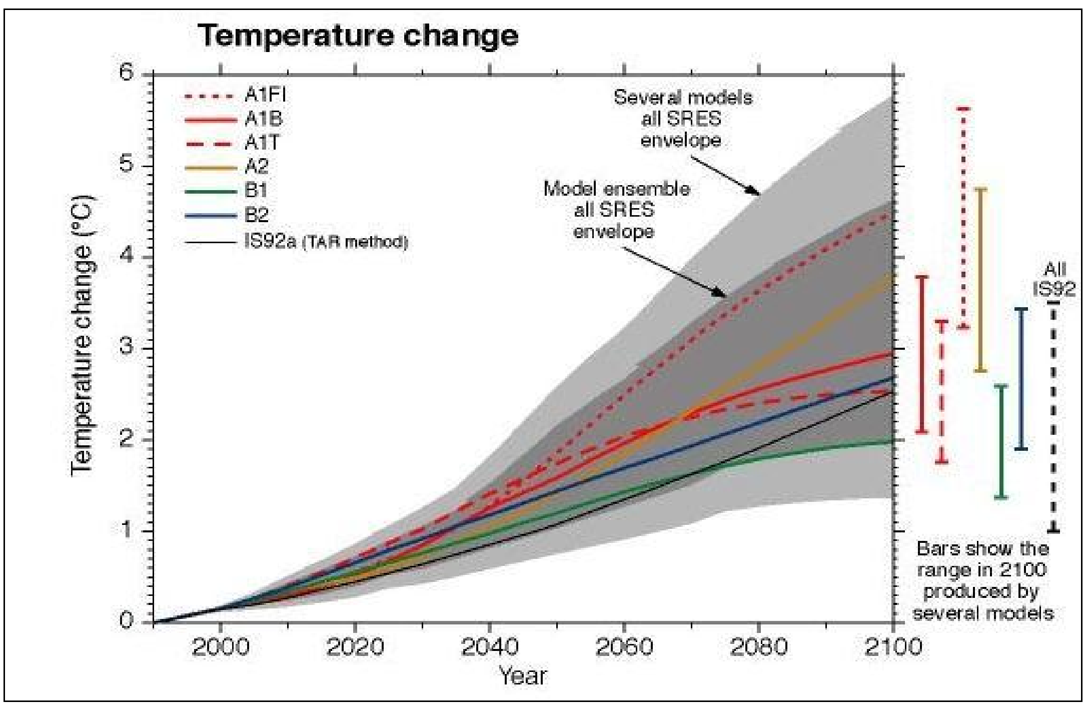


Figure 7.10: The range of the global average temperature projections for six SRES scenarios using a simple climate model (Source: IPCC, 2001a, p.70).

GCM results become less reliable at higher spatial resolutions so that uncertainty increases as the spatial scale of focus decreases, e.g. going from country to regional and local scales, such as Gassim. Whilst Hulme et al. (2002) stressed that most GCMs produce data at 300 – 500 km resolution, and hence uncertainty arises from the need to fill in the missing regional detail such as mountains, coastlines, lakes and inland seas which might affect the local situation. Tubiello (2000) also asserted that GCM scenarios are less reliable at small spatial scales. The results for Gassim have been based on the output for one grid box, which would not be reasonable for climatological assessment (this requires multiple grid points). However, for an applied agricultural study, the use of one grid box is acceptable whilst acknowledging the uncertainties.

Uncertainties also arise when generating impacts from climate scenarios. Section 7.5 highlighted the differences related to using different climate variables to estimate ET_O. This is also the case for different ET_O estimation methods (e.g. PM and Thornthwaite). Also this study has not directly addressed the complex and uncertain effects of enhanced atmospheric CO_2 enrichment on stomatal conductance. IPCC (2001c) reported that there is a large degree of uncertainty over the effects of CO_2 enrichment on catchment-scale evaporation. It is difficult to transfer findings from laboratory greenhouse conditions to the real world where there are many other interacting factors (IPCC, 2001c). Most climate impacts studies to date have assumed no change in stomatal conductance. Finally, there are some uncertainties related to the methods for estimating CWR and measuring / estimating irrigation efficiency in the field (Chapter 5), these include assumptions about actual irrigation water use and theoretical estimates of field water use efficiency.

7.9.2 Integrating the Effects of Future Climate Change with Non-Climate Challenges in Irrigation Water Management

IPCC (2001c, p. 31, 195) reported that:

> *''Non-climate changes may have a greater impact on water resources than climate change [...] at the outset, it is important to emphasize that climate change is just one of many pressures facing the hydrological system and water resources''.*

This section discusses the importance of climate change relative to the other challenges facing water management in the area. The climate change effects on CWR presented here are relatively low compared to the influence of other factors, particularly differences between the methods that the farms use to manage and apply irrigation water. It is also important to note that the range of uncertainty in the effects of future climate change impacts is often far larger than the actual size of the impacts, as is the case here. For example, the irrigation efficiency of Gassim farms is low, ranging from 20% to 59%, meaning that potentially up to 41% to 80% of the water does not contribute to the production of food (assuming no re-use or recharge of groundwater). On a global scale, Ragab et al. (2002) postulated that the overall average efficiency of agricultural water use is as low as 40% (although these figures are still debated; Seckler et al., 2003). Low values of IE reveal that non-climatic factors have a very strong bearing on water supply. Improvements in technology and management will be important regardless of climate change.

There is a large difference between the AWA and GIR which on average is 55%. This means that farmers at present use much larger quantities of water than what is actually required by the crop. This difference is currently larger than the effects of a temperature warming of 4.1°C by the 2080s. Frederick et al. (1999) stated that uncertainties may exist with converting large-scale climatic changes into specific regional impacts due to uncertainties with models and data, and also

because many of the human impacts will depend on economic, technological, and institutional (i.e. non-climate) factors that define water systems.

Clearly, non-climatic factors such as crop water management are significant relative to the marginal effects of climate change, projected here for the short-term. Non-climate factors will probably outweigh climate change in determining future demand and use of water. There is no doubt that the issue of IE is an important consideration when planning sustainable water resource use. Even more important will be government policies towards agricultural subsidies and water charging.

7.9.3 Conclusions

This chapter has described the possible ramifications of climate change on ET_O and CWR in the Gassim area. The climate change scenarios were from three GCMs (HadCM3, CGCM2, and ECHAM4) with two scenarios for two study time horizons, the 2020s and the 2080s. The study analysed winter wheat as a typical crop but the approach is also applicable to other crops and to other regions in Saudi Arabia. This is first study of climate change in Gassim, and there have only been a few very general studies of climate change in Saudi Arabia. It is therefore not possible to compare the results of this study with others in Saudi Arabia.

The main results of this chapter are listed below:

- On average a 1.3°C rise in temperature by the 2020s increases the ET_O by 3%, and a 4.1°C rise in temperature by the 2080s increases ET_O by 12% (A2), and 9.2% (B2).
- The many uncertainties associated with climate impact studies were reviewed and are emphasized here so that these results should be treated carefully and not as predictions.

- By the 2020s higher ET_O could lead to an increase in CWR by 3%, and by the 2080s, by as much as 12% (A2), and 9% (B2). Under these conditions Gassim will have higher irrigation needs than under the current climate, which, all other things being equal, will worsen water management challenges.
- Sensitivity analysis shows that ET_O is most sensitive to change in temperature, followed by wind speed. A 1°C increase in temperature could result in an increase in CWR of about 103 m^3/ha/season for wheat in the study area. On the other hand, ET_O is not particularly sensitive to relative humidity. The sensitivity of ET_O (Penman-Monteith) is affected by the specific values of input climate variables.
- Under the projected climate change, the theoretical LWGS for wheat will be reduced by between 9% and 26%, relative to the baseline because of high temperatures, so how this may affect the actual LWGS or farmers' practises may be a little different and depend on the farmers responses to extreme temperature.
- A questionnaire revealed that the farmers who grow wheat in the Gassim area unanimously agreed that the greatest problems that they face are not from climate variability but from grass and weeds and the costly herbicides that they needed to suppress them. The climate, particularly high temperatures, is mentioned by farmers to be of secondary importance primarily because they have to irrigate their wheat crops in order to reduce the effects of extreme temperatures.
- In light of the probable consequences of climate change in the Gassim area, this study speculated on the likely measures that could be adopted to protect against such impacts through adaptation strategies. Probably the most efficacious measure would be water-pricing as once the government starts charging for irrigation water improved farming practices should follow.

Government policy towards agricultural subsidies will be critical for future water use.

- This study concludes that non-climate factors, such as the water used by farmers, will greatly influence the consequences of climate change in determining the state of water demand in the study area. For example, there is a large difference between the AWA and GIR which on average is 55%. This means that farmers at present use much larger quantities of water than what is actually required by the crop. The difference is currently larger than the effects of a temperature increase of 4.1°C by the 2080s.
- Finally, in Chapter 5 this study measured water use and IE in Gassim area in the TFs and CFs, followed by Chapter 6, which assessed the climate change in Saudi Arabia and in the study area. Whereas, Chapter 7 is looking for the implication of climate change and its impacts on irrigation which may be considerable owing to the location of the study area in an arid zone. Chapter 5 have shown there are differences between CWR and AWA because of the local management practises of the farmers. Therefore, the effect of climate change will have a physical effect but also will depend heavily on the management of the crop.

Chapter Eight: Discussion of Possible Responses and Conclusions

8.1 Introduction

The IPCC (2001c) reported that average global surface air temperatures have increased by 0.6 ± 0.2°C over the 20th century, and projected that average temperatures will warm by 1.4° to 5.8°C by 2100 relative to 1990. These changes in temperature will have consequences for rainfall, ET_O and CWR. In the Gassim area of Saudi Arabia one of the main concerns about climate change is its possible effects on the increased demand for water in the domestic, agricultural and industrial sectors. Water resources in this area are limited and already under pressure from high demand, particularly for irrigated agriculture.

How will national agricultural policies be affected by climate change? Existing policies have already caused the need for drinking water to be obtained from coastal desalination plants, or required the government to import water from neighbouring countries. In this context, this study has investigated Gassim's most important agricultural interest, namely wheat.

This study represents the first integrated study into the possible effects of climate change on agricultural water use in Saudi Arabia. The results are of interest to irrigation and farming practice in the region in relation to the possible implications of climate change for their activities. This chapter draws together the main findings from the preceding chapters to produce a more integrated assessment of the interaction between climate variability and change and agricultural water use in Gassim. The previous chapters are summarized and the results brought together to discuss the implications of climate change for water use in Gassim in relation to

possible adaptation strategies in the sector.

The overarching aim of this study was to examine agricultural practices and irrigation water use in Gassim in relation to their sensitivity to climate change. This has involved a review of climate variability and water resources in the Gassim area. Followed by a comparison of water use practice in TFs and CFs by estimating ET_O and CWR of wheat. The objective was to consider conditions under actual climate and evaluate the efficiency of irrigation water use on two types of farms. The aim was then to investigate climate change scenarios for the study area to assess the potential impacts on ET_O, CWR and LWGS over the short-term (2020s) and long-term (2080s) to provide an indication of the possible effects of on water demand and agriculture.

8.1.1 Recent Climate Variability in Gassim

In order to place the possible effects of climate change into perspective it is important to consider the extent of recent climate variability and its possible role in affecting agricultural activities. Chapter 4 therefore investigated recent climate variability and recent trends in water recourses in Gassim. The main findings are as follows.

Linear trend analysis was performed on climate series (temperature and rainfall) for the main station records in the study area. A gradual increase in the observed average annual temperature is clear during the period 1970 – 2000 the average rate of warming over this period is about 1.5°C. (Tmin is 0.3°C/decade and Tmax is 0.7°C/decade). Percentile analyses of daily Tmax and Tmin for winter and summer shows that the number of very warm days and nights has increased slightly, and the number of very cool days and nights has decreased slightly (using five indicators) This supports a general picture of warming and increased frequency of relatively extreme temperature events in Gassim.

The average annual rainfall is a very low (92 mm), the highest average annual rainfall of the eleven rain gauges in the study area is 113 mm, and the lowest is 66 mm. The trend of the annual rainfall for eleven rain gauges indicates a positive trend over the full period, with the average rate of increase about 3 mm/decade. This trend is considerable in relative terms as the total annual rainfall is only 92 mm, but very small in absolute terms. The average annual Class A pan evaporation is about 3393 mm/year. Increasing temperatures produce a small positive trend in evaporation.

8.1.2 Recent Trends in Groundwater Levels in Gassim

Economic activity in Gassim is almost entirely dependent on local aquifers, which are barely replenished by the low rainfall (fossil groundwater). The aquifers are being depleted by abstractions for irrigation; this situation has caused the groundwater levels to drop continuously for several years in most of the study region. For example, there has been a 71 m fall in the water level in over 23 years in the only well with a long record available. In four other wells the water level has declined by between 5 and 12 m from 1997 to 2002. This can be compared with the Al-Hasa area to the south-east of Gassim where the decline is as much as four m per year (Omran, 2004). Consequently, if this pressure on the water supply continues, even without climate change, the study area will face severe shortages in water supplies with severe consequences for agricultural production.

8.1.3 Estimating Irrigation Water Use and Measures of Irrigation Efficiency

Chapter 5 presented a quantitative evaluation of water use for a winter wheat crop, under two types of irrigation systems modern: sprinkler irrigation; and traditional open furrow. Field observations during one season in 2003 identified significant differences between the TFs and CFs in terms of AWA and productivity. The AWA

at the TFs was between 12663 (with uncertainty range of ± 2532) m^3/ha/season and 18874 (with uncertainty range of ±3775) m^3/ha/season but the productivity of wheat ranged from only 1.6 to 2 ton/ha. On the other hand, in the CFs, the AWA was 7100 and 9341 m^3/ha/season and the productivity 4.2 and 6.3 ton/ha (only two farms studied). The estimates of AWA especially in the TFs, are subject to some uncertainty as AWA partly depends on information supplied by the farmers during fieldwork. This specifically relates to the frequency of irrigation during the season and the length of time for each irrigation, for which some farmers relied upon experience and recall without a high level of accuracy. This necessitated taking an average of each farmer's response, which may have partly contributed to the large differences in AWA between the TFs, despite all farms having similar environments, e.g. soil and climate. Consequently, an upper and lower range is shown that represents (±20% errors in the AWA estimates) which is the possible magnitude of uncertainties and random errors in the estimates of AWA.

The FAO Penman-Monteith method (FAO-PM) (Allen et al., 1998) was used to estimate ET_O. The average LWGS is about 130 days, so the total seasonal ET_O for the wheat crop variety (Yecora Rojo) lies in the range of 406 mm/season for Farm 1 to 640 mm/season for Farm 4 due to differences in planting date, and so commencing early sowing conserves water use considerably. This is because the CWR values are affected by the higher temperatures later in the growing season. CWR therefore ranges from about 3038 m^3/ha/season (early season) to 5188 m^3/ha/season (late season), respectively. In addition, in order to maintain acceptable soil salinity levels, all eight farms require leaching of salts, ranging from an extra 2% to 39% to the CWR/season.

In terms of irrigation efficiency, it was found that FWUE values are low. They range from 0.1 to 0.2 kg/m^3 in the TFs, 0.6 and 0.7 kg/m^3 at the two CFs. Moreover, CWUE values are also low, ranging from 0.2 to 0.4 kg/m^3 at the TFs, and 0.8 and 1.4 kg/ m^3 in the CFs. Estimates of IE are quite low, ranging from 20% at Farm 1 to 60% at Farm 7. Observation and measurements highlighted that the

main sources of low IE are the volume of applications and the method of irrigation in the TFs. However, it must be noted that some of the losses may not be absolute losses, as excess water may percolate and recharge groundwater or in some cases be returned to canals and be re-used.

8.1.4 Scenarios of Climate Change for Saudi Arabia and Gassim

Results were examined from three different GCMs, with two emissions scenarios (A2 and B2) for two study periods. Changes in variables which affect ET_o (temperature, relative humidity, wind speed and sunshine) were calculated for the whole of Saudi Arabia and in more detail in Gassim using the results from the HadCM3, CGCM2 and ECHAM4 climate models. Significant increases in annual temperature were projected from 0.4° to 1.6°C by the 2020s, and about 2° to 4.8°C by the 2080s. In terms of annual rainfall for all Saudi Arabia there were no clear trends in either period. Overall, the changes range between -20 and +30 mm/year relative to the baseline period of 1971-2000. The rate of warming for the grid box overlying Gassim was similar to the average results for all of Saudi Arabia. The results for the other variables showed small inconsistent changes with less significance for ET_o than the temperature warming.

Percentile analyses were applied to daily temperature series from HadCM3. The annual Tmax and Tmin increase continually during the 2020s and the 2080s relative to the baseline climate. The rise in Tmax and Tmin in the future climate during the summer is principally associated with a reduction in the frequency of very cold days. The threshold 1st , 5th, 10th ,90th, 95th and 99th percentiles of Tmax for winter and summer increase by the 2020s by 1.2°C and 1.5°C, respectively, and by the 2080s by 4.6°C and 3.4°C, respectively. Also Tmin for winter and summer increase by the 2020s by 2.5°C and 1.5°C, respectively, while by the 2080s it will be about 4.3°C and 3.3°C, respectively.

In terms of rainfall, the results from the GCMs show that the climate scenarios vary from model to model, with little consistency in their output e.g. HadCM3 produces a small decrease in each period ranging from -1 to -14 mm/year. However, CGCM2 produces an increase under scenario A2 of about 21 mm/year (2020s) and 12 mm/year (2080s), and with scenario B2 3 mm/year (2020s) and 10 mm/year (2080s). ECHAM4 produces increases in rainfall larger than those with CGCM2 in both periods and emissions scenarios at 18 mm/year and 20 mm/year, respectively, by the 2020s; and 25 mm/year and 23 mm/year, respectively, by the 2080s.

These scenarios are subject to uncertainties reflected by the differences between models and emission scenarios, and consequently should be interpreted with caution (see Section 7.9). However, to date there has been no other research that discusses climate change in any detail based on the output of GCMs, for the study area and even for Saudi Arabia as a whole. There are no guidelines, little or no national literature, and no other studies to compare the results of this study with.

8.1.5 Implications of Climate Change for Irrigation Water Use

Given these changes, how important is future climate change likely to be for water use and management in the region? Chapter 7 presented the possible impacts of climate change in the study area, using winter wheat as a typical crop. Nevertheless, the conclusions are more generally applicable to other crops and to other regions in Saudi Arabia. The potential impacts were assessed by incorporating changes in ET_O (temperature, relative humidity, wind speed and sunshine duration) into estimates of CWR and the potential impacts of climate change on the LWGS.

In terms of ET_O and CWR, warming is estimated to increase ET_O and CWR by 3% with 1.3°C increase in average annual temperature by the 2020s. Additionally,

a 4.1°C rise in temperature by the 2080s could increase ET_O and CWR by 12% under scenario A2, and 9% under scenario B2. Given these changes and assuming no change in agricultural practise Gassim would have higher irrigation needs than under the current climate conditions, which will put the area under greater water availability pressures.

With climate change for example, a 1°C increase in temperature, could lead to an increase in ET_O of 0.12 mm/day and 0.14 mm/day in January and July, respectively. This could amount to about 103 m^3/ha/season additional water need for irrigating wheat every season. In other words Farm 8 with a wheat area of 2850 ha would need a further 293,550 m^3/farm/season.

The sensitivity of Penman-Monteith ET_O to variations in the input parameters indicates that ET_O is most sensitive to temperature, and wind speed, e.g. a 1°C increase in temperature could result in an increase in CWR of about 103 m^3/ha/season for wheat in the study area. On the other hand, ET_O was not particularly sensitive to relative humidity compared to other studies which have highlighted differences in sensitivity according to climate conditions (see e.g. Martin et al., 1989 and Arnell, 1996). Daily temperature output from HadCM3 produced decreases for the theoretical LWGS for wheat by between 9% and 26%. But it should be noted there are some uncertainties in this context; in particular the study does not directly address the complex and uncertain effects of enhanced atmospheric CO_2 enrichment on stomatal conductance.

The possible measures that could be adopted to reduce the impacts through adaptation strategies were presented and are discussed in Section 7.8.

The finally section concludes with a set of recommendations for water authorities and their water management, making adjustments to conserve and improve the water resources management in the area.

8.2 Some Policy and Farmer level Responses for Improving Water Management in The Face of Increasing Water Scarcity and Climate Change

In order to tackle the existing water shortages and, their possible exacerbation by climate change, and poor water management in the study area, a range of potential strategies could be adopted. These take two different perspectives: supply side management (traditional/physical responses) and demand side management (policy/economic responses etc). A combination of supply-side and demand-side management may be the best approach, although supply is already greatly limited. These aims could be achieved by the prudent adoption of some of the measures listed in Table 8.1.

Demand Side	Supply Side
• Charging for water. • Public awareness. • Increasing irrigation efficiency. • Government licenses for digging wells. • Changing crop patterns and government subsides in agriculture • Improving irrigation methods. • Growing crops that need less irrigation. • Increasing crop drought-tolerance (IPCC, 2001c).	• Finding new aquifers. • Conducting a new and highly accurate hydrology survey over Saudi Arabia. • Building new dams. • Increasing water recharge rates. • Managing water resources more efficiently. • Increasing desalinization.

Table 8.1: Some examples of adaptive techniques in water resources management.

Some of the following are both supply and demand, and are discussed in more detail below.

8.2.1 Government Policy for Wheat Production and other Crops

In terms of demand for water existing government agricultural policies are the main influence. Wheat production is currently one of the heaviest consumers of water in Saudi Arabia, and this is particularly so in the Gassim area. Wheat is also the most economically important crop in the country. This commercial enterprise is almost entirely supported by government grants, in order that Saudi Arabia can compete successfully with more water abundant countries. Consequently, Saudi Arabia has become the world's sixth largest wheat exporter, through a process which may be described as artificial agriculture. It has taken a few decades for policymakers to realize just how dramatically this practice is affecting the groundwater reserves. Saudi Arabia uses 80% of its fresh water for agriculture, and the Ministry of Planning (1990) reported that water consumption by wheat alone was estimated at 5.3 billion m^3, which represented 37% of the agricultural sectors' total water demand in 1987.

Subsidies for wheat production on large commercial farms are the main drivers of water use. Changes in this policy could benefit both the country's water and financial resources as the water is more costly than the wheat produced. Moreover, mineral water in Saudi Arabia is more expensive than oil; $ 0.3/litre, compared with $ 0.2/litre, and it would therefore be more cost effective for the government to import wheat than to subsidize its own production. Indeed, there is a growing body of opinion now arguing this case in Saudi Arabia. Al-saleh (1992) also reported that one kilogram of wheat costs the government more than $ 0.80, which means that it is cheaper to import wheat than to grow it. Moreover, TED (2004) estimated that wheat in Saudi Arabia is grown at eight times average world prices. Al-Qunaibet (2001), a hydrologist and government adviser, estimates that

by ceasing wheat production this would save about $ 267 million/year and about 4000 million m^3 of non-renewable groundwater.

At present, government policies are now subsidizing palm tree production; by $ 13.3 for each palm tree grown. The problem is that palm trees are a long-term investment and consume more water than wheat; at 37910 m^3/ha/year (Abderrahman et al., 1993), against 3927 m^3/ha/season for wheat. This means that the new policy will consume about 90% more water per year than wheat when using the surface irrigation method for palm trees in the current climate (about 83% when using the drip irrigation method). In addition, climate change may increase this crop's use of water which will lead to added pressures on water resources. There is, therefore, clearly a need to integrate agricultural planning and policies with the water sector.

8.2.2 Improve Water Management Policies

Water is still free of charge in the agricultural sector. This has contributed to inefficient use of water, and therefore policymakers should review and re-evaluate the legal and economic approaches to managing water resources. The aim should be to urge farmers to use modern irrigation methods and to irrigate only according to the crop requirements. Al-saleh (1992) suggested that monitoring water consumption for agricultural purposes should become an ongoing commitment.

The most efficacious measure is likely to be the introduction of, or increases in, water pricing. Shiklomanov (1998) and Oweis et al. (2003) concluded that one could expect efficiency to improve partly as a result of changes in the cost of water (see Section 7.8). However, in order to implement such changes, which would involve some very sensitive issues, strategies will need to be carefully considered. Farmers questioned about whether they have any incentives to reduce water use said that at the moment they have no incentive to do so because their water is free of charge. In addition, the labourers who work in the farms are paid without any

regard to the yield or to how much water (or fuel) they use. These factors could be changed by policymakers. Subsidies are also given to farmers without any evaluation of their water management skills or of how much they produce; this could also be changed.

The government (agricultural sector) can respond quickly and in a large degree if it needs/wants to, e.g. production of wheat in 1984 was about 1346843 tons, by 1986, production had risen to 2213152 tons and by 1991 had reached 4 million tons, which indeed is an enormous increase.

8.2.3 Improve and Enhance Agricultural Technologies, Crop Choice and Management

Assuming that farming in Saudi Arabia is a worthwhile economic activity, policymakers could encourage farmers to utilize and expand greenhouse farming as much as they can, especially for vegetable growing. Using greenhouses for cultivation is more efficient for water use especially with micro-drip irrigation systems. They also protect crops from adverse weather conditions, particularly high rates of evaporation and extremes of temperature. Alkolibi (2000) indicated that about 30% of vegetable crops in Saudi Arabia are already produced in greenhouses. Farmers, especially in the CFs, could also have links with local weather station forecasts in order to help them avoid unnecessary irrigation, particularly in the wet season.

This study found that the early sowing of wheat conserves water use considerably in the study area. For example, estimated seasonal CWR between the early (15^{th} November) and late seasons (15^{th} January) is about 3038 m^3/ha/season, and 5188 m^3/ha/season, respectively. Early sowing may also protect the crop during the anthesis and grain filling stages from the excessively high temperatures at the end of the season.

8.2.4 Some Supply Side Options

This study and many others highlight the major decline in groundwater level. For example, all farmers who were questioned noted that groundwater levels are declining dramatically; many farmers have had to extend their pipes inside the wells. Responses to aquifer depletion include a variety of methods, e.g. building more dams, reducing the irrigated area, and improving water management and even artificial rainfall. Alkolibi (2002) suggested that replenishment of aquifers could be achieved by utilizing the large number of reservoirs scattered across the country and by taking advantage of surface runoff. This could be done by constructing a network of pipes linking reservoirs to the aquifers, or by refilling aquifers through digging large wells at the ends of the major aquifer valleys and basins.

Another options chosen by the Saudi government has been to build desalination plants; there are now about 28 desalination plants in the country, producing some 2.5 million m^3/day (Albayan, 2002), and meeting 70% of Saudi Arabia's drinking water needs (Saudi Arabia Information Centre, 1996). However, this option is very expensive, and makes the Kingdom particularly vulnerable in terms of conflict such as war or terrorist attack. Also in response to the approaching shortages of water, the government constructed more than 190 dams by 1999, in different areas and with a combined storage capacity of approximately 475 million m^3 (Abdulrazzak, 1995). The government, at all levels should take this issue seriously, especially in high risk areas, and strategic planning should be adopted before the situation becomes critical.

8.3 Summary

Finally the main results of this study can be summarised as follows:

- The average rate of warming over the 30-year period 1970 – 2000 in the study area is about 1.5°C.
- There is a very slight positive trend in annual rainfall for the period 1971–2000, and the average rate of increase was 3 mm/decade.
- The groundwater table has dropped continuously over the past couple of decades in most of the study region. For example, this study presented recorded a 71 m decline in the water level of one particular well over 23 years.
- The total seasonal ET_o for the wheat crop (Yecora Rojo) is estimated to lie in the range of 406 to 640 mm/season (differences due to planting dates).
- Wheat CWR in the early and late seasons is estimated to be about 3038 m^3/ha/season, and 5188 m^3/ha/season, respectively.
- FWUE values are low, ranging from 0.09 to 0.17 kg/m^3 at the TFs, and 0.59 to 0.67 kg/m^3 at the CFs.
- CWUE values are also low, ranging from 0.24 to 0.42 kg/m^3 at the TFs, and 0.84 and 1.42 kg/ m^3 in the CFs.
- IE values are low, ranging from 19.6% at Farm 1 to 59.2% at Farm 7. Observation and measurements highlighted that the main reasons for poor efficiency are the management systems and the irrigation methods employed.
- Much of the water loss may not be absolute as excess water might percolate and recharge the groundwater, or in some cases be returned to canals and be re-used.
- Future warming rates for Gassim derived from three GCMs by the 2020s are between 0.99°C and 1.54°C higher than those currently observed, but by the 2080s, the range is between 3.15°C and 4.89°C higher.

- In terms of rainfall, HadCM3 produces a small decrease, whereas CGCM2 produces a small increase, and ECHAM4 produces increases in rainfall larger than CGCM2.
- Future ET_O and CWR increase by 3% per 1.3°C increase in average annual temperature by the 2020s, and by the 2080s this range is between 9% and 12%.
- The future LWGS will decrease by between 9% and 26%, relative to the baseline. According to the wheat farmers who were questioned, the main constraints on agricultural practice in the study area are grass and other weeds, and the cost of herbicides. They also complained about of the cost of electricity and fuel, although some did mention problems due to higher temperatures and the increasing salinity of their groundwater.
- Regarding climate change, the farmers in the study area are not so concerned, and for many farmers it is not as big an issue as the supply of water and its efficient use.
- The most efficacious measures to mange water sustainably and adapt to climate change could be water-pricing and changes to national agricultural subsidies.
- Changing and improving water management will improve water use efficiency and that should be enough to cope with the increasing demand for water due to climate change, as the increases in CWR are small when compared to the inefficiencies present in existing water use.

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